

# 7. A geographic information system-based sand and dust storm vulnerability mapping framework

## Chapter overview

This chapter provides a sand and dust storms (SDS)-focused process to assess vulnerability using geographic information system (GIS) procedures where data availability or quality is not a critical issue. The chapter provides a flow chart for GIS-based vulnerability assessment and conceptual models of how SDS affect the health, socio-economic, environmental and agro-ecological domains of a vulnerable area (from local to global). Detailed attention is paid to the selection of vulnerability indicators (including tables of possible indicators). The chapter includes specific formula to produce vulnerability maps using a GIS platform.

This chapter should be read in conjunction with chapters 3, 4, 5 and 6.



## 7.1 Overview

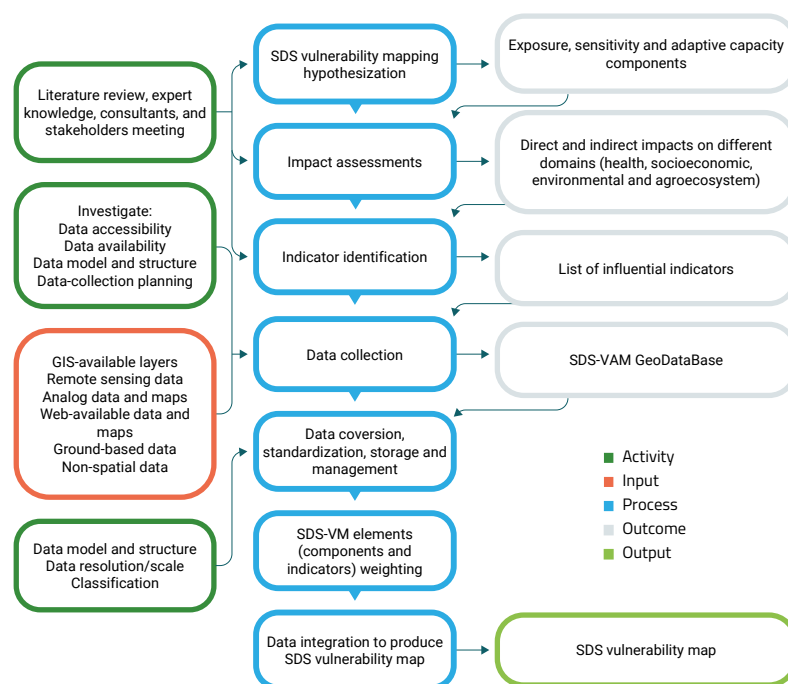
This chapter describes a procedure for a geographic information system (GIS)-based mapping of vulnerability to sand and dust storms (SDS). The goal is to elaborate this procedure in detail and strengthen the users' ability in understanding practical considerations on data-collection and analysis using a GIS for SDS vulnerability mapping.

As noted elsewhere, data availability and access differ among countries and stakeholders of SDS. The proposed procedure is intended to be applicable and adaptable in different circumstances. This assures that even with limited data accessibility, a basic map of SDS vulnerability can be achieved.

Vulnerability, its components and the relevant indicators exhibit such a large and complex spatial-temporal variability that an interactive GIS-based platform is required to handle them. Accordingly, stakeholders having uneven profiles of data, skills and abilities will be able to adapt this mapping procedure.

This adaptation is closely linked to the level of integration of relevant data, such as GIS layers, remote sensing data, available web data and non-GIS information, into the procedure. To do so, limitations and shortcomings of implementing GIS for sand and dust storm vulnerability mapping (SDS-VM) should be well understood. These limitations include a lack of data, available data not being in GIS format and GIS data having no uniform data model and structure, among other scenarios.

Mapping SDS vulnerability can be subjective if the experiences and opinions of experts and stakeholders are inserted into the procedure (for example, by selecting different sets of indicators) and can create different vulnerability maps for the same SDS phenomenon. It is therefore necessary to propose a general procedure that can provide objective estimates of vulnerability, unbiased towards different users or environmental conditions. The stepwise procedure and the order of specific steps required to implement the procedure are illustrated in **Figure 17**.



**Figure 17. A flowchart of geographic information system vulnerability mapping**

## 7.2 Approaches to an SDS vulnerability mapping and assessment framework

The complex and multidimensional nature of vulnerability makes any mapping methodology framework arbitrary, overlapping and contentious to a degree, depending on disciplinary differences in how to formulate vulnerability (Intergovernmental Panel on Climate Change [IPCC], 2012a). The majority of vulnerability assessments and mapping developed over the past decades involve statistical analysis, designing vulnerability indices and the use of GIS (United Nations Environment Programme [UNEP], 2003).

The empirical-statistical approach is based on the statistical analyses of observed damage data and distributions from past hazard events. Statistical data and techniques (for example, regression, correlation, normalization and statistical indices) are commonly used to identify vulnerable communities and develop composite indices. Such indices combine several particular indicators and deliver simple and usable results from a vast amount of diverse information.

The indicator-based approach estimates the overall vulnerability from a set of indicators representing interactions between hazard and system elements. Indicator-based vulnerability is flexible and applicable to different hazards and it can be easily adapted to user needs (Kappes et al., 2012). However, there is a need to base indicators on evidence or proven models, otherwise they should be used cautiously as a tool for decision-making. Most vulnerability assessment and mapping indicators are model driven and not data driven, making them susceptible to a degree of uncertainty.

Composite indices make the information easily usable by potential users, including governments and public sectors. For instance, the Committee for Development

Policy (2000) and the Caribbean Group for Cooperation in Economic Development and the World Bank (2002) used statistically normalized variables with equal weights to construct composite vulnerability indices. However, despite their simplicity and directness, composite indices are prone to delivering poor outcomes in the absence of evidence or evidence-based models. While commonly used, composite indices are often flawed by linking and combining different indicators into one resulting value.

On the other hand, GIS offers a flexible and useful tool to show the spatial distribution of vulnerable regions and communities. By relying on analytical frameworks and proven models, such an approach leads to accurate results. GIS can accept data derived from a variety of sources such as satellite imagery, aerial photography and spatially referenced maps and associated tabular attribute data. This is critical, since data might be collected in different ways and integrated in different forms.

Furthermore, GIS provides a powerful platform for geostatistical/geospatial analysis, as well as visualization and mapping tools. Examples of GIS-based vulnerability mapping are the:

- Climate Change Vulnerability Map, an interactive online GIS platform ([http://maps.massgis.state.ma.us/map\\_ol/cc\\_vuln.php](http://maps.massgis.state.ma.us/map_ol/cc_vuln.php)) provided by the Massachusetts Department of Public Health, Bureau of Environmental Health
- Interactive map of Central America presenting vulnerability to different natural hazards prepared by UNEP/GRID Sioux Falls (1999)
- Food Insecurity and Vulnerability Information and Mapping Systems (FIVIMS), developed by Food and Agriculture Organization (FAO) (1998)

## 7.3 Key concept of vulnerability assessment and mapping

### 7.3.1. Vulnerability

The word “vulnerability” has different applications and interpretations in different disciplines. “Vulnerability” may refer to “biophysical vulnerability” that is closely aligned with the concepts of “hazard”, “exposure” or “risk”, or it may highlight the socioeconomic and cultural processes that are more in line with the concepts of “resilience”, “coping capacity”, and/or “adaptive capacity” (Preston and Stafford-Smith, 2009). There might also be integrated conceptualization of vulnerability, considering both biophysical and socioeconomic factors that collectively create the potential for harm. Considering only components of biophysical vulnerability (that is, only exposure and sensitivity), regardless of adaptive capacity, can lead to biased estimates of vulnerability and, consequently, an erroneous policy implication (Piya et al., 2016).

Given the multidimensional and complex nature of SDS, it is necessary to consider vulnerability as a function of three interactive components: (i) exposure to change; (ii) associated sensitivities and (iii) related adaptive capacities (Polsky et al., 2007). The first two components directly influence vulnerability so that the more the exposure or sensitivity, the greater the vulnerability.

On the other hand, adaptive capacity is inversely related to vulnerability, thus, an increase in the adaptive capacity will result in lower vulnerability. Multiple definitions exist for the components in different disciplines and the distinctions between them are not always clear. All components, however, are site- and system-specific and vary over time. The three components of vulnerability are explained in the next sections.

### 7.3.2. Exposure

“Exposure” refers to the nature and degree to which elements of a system are at risk of a natural or human-induced hazard (IPCC, 2012b). Elements at risk could include individuals, livelihoods, ecosystems and resources, infrastructure, environmental, agricultural, economic, and social assets (IPCC, 2014b). Gender, age and health status should also be considered in establishing exposure. Exposure can be considered geographically by identifying the location, characteristics, number and type of elements exposed to hazard or harm. Although sometimes used interchangeably in the literature, there is a distinct difference between vulnerability and exposure.

Exposure can be regarded as a necessary, but not sufficient, determinant of vulnerability (IPCC, 2014a). This means that there might be elements exposed to hazards but that are not vulnerable, while to be vulnerable, it is necessary to be exposed to hazard. Information on exposure is of vital importance for vulnerability assessment to address how at-risk elements of a given system act when subjected to hazard. In the case of SDS, frequency, intensity and duration of exposure to the events are also critical, as they will increase the likelihood of risk for the given elements.

### 7.3.3. Sensitivity

Sensitivity is another concept related to vulnerability, defined as the degree to which a system is modified or affected by hazard stimuli (IPCC, 2014a). Depending on their characteristics, various systems react differently to the same hazard event. For example, a system might be vulnerable to flood, but not to drought. Sensitivity determines how different elements in a given system respond when hazard events occur.

For a given system, sensitivity can either be limited to identifying whether the system is sensitive to a hazard/perturbation or, in

a more comprehensive way, to measure the degree of sensitivity. Sensitivity can also be used to rank different elements of the system based on their sensitivity to hazard/perturbation. Exposure and sensitivity are closely connected determinants of the vulnerability of a system and dependent on the interaction between the characteristics of the system and the attributes of the hazard stimulus (Cutter et al., 2009).

### 7.3.4. Adaptive capacity

While exposure and sensitivity determine the scale and nature of likely impacts caused by hazards/perturbations, the adaptive capacity of the system quantifies its ability to cope with, manage, recover, and adapt to the potential adverse impacts (IPCC, 2014a). Adaptive capacity, in general, can be expressed as the process, action or state in a system (individual, community, sector and country) to better cope with, recover and adjust to changing conditions and risks.

In the context of SDS, adaptive capacity of a system is seen as adjustments in ecological and socioeconomic behaviours in response to potential or actual SDS events to reduce society's vulnerability. Due to the variability in SDS impacts and consequences, adaptive capacity tends to be context-specific, meaning that it varies from situation to situation, among societies and individuals presenting temporal and spatial variation. Gender, age and health status need to be considered in defining adaptive capacity.

## 7.4 Impact indicators of SDS for vulnerability mapping

### 7.4.1. Measuring vulnerability

Vulnerability is not an intrinsic property of a system to be directly observed or measured. Instead, it has to be deduced through a set of variables (indicators) estimating exposure, sensitivity and adaptive capacity. A common practice to estimate vulnerability is to use surrogate

measures of vulnerability components and then aggregate them to yield the overall vulnerability "score".

Different vulnerability assessments can be classified based on the vulnerability factors that they consider (Füssel, 2007). Human and natural systems are fundamentally interlinked and risks to one would eventually translate into risks to the other (UNEP, 2003).

This means that the measure of vulnerability should include factors from both humans and the environment, plus the associated risks to both.

The United Nations Inter-Agency Secretariat of the International Strategy for Disaster Reduction (UN/ISDR) (2005), for instance, classified four groups of vulnerability factors associated with hazard reduction: physical, economic, social and environmental. Vulnerability factors, in turn, can be inferred from the impacts of hazard on different aspects of system. Accordingly, in this document, the impacts of SDS are grouped into four main domains including human health, socio-economy, environment and agroecosystem.

Each domain has a number of subdivisions, which map out the major elements of interest. These impacts are then used to select the ultimate set of indicators to assess SDS vulnerability and produce maps. The mapping process also needs to discern how vulnerability may differ by the gender, age or health status of the individuals being assessed.

### 7.4.2. Human health

SDS threatens human health and safety in many ways, by affecting the environment that provides us with clean air, food, water and security (Goudie, 2014). Assuming that the impacts of SDS are projected to increase over the coming decades, current health threats will likely persist and intensify. The health impacts of SDS are dependent on:

- the location of human populations with respect to the emission sources of SDS and the downwind direction of dust transport and deposition
- the amount of suspended materials that SDS contain
- particle sizes and chemical compositions (ibid.) and the health status of the vulnerable population

There are generally three types of health impacts:

- **Type 1.** Medical and physical health
- **Type 2.** Mental health and well-being
- **Type 3.** Community health

Type 1 considers human health impacts of air pollution and contamination pathways caused by SDS. Depending on their origins and pathways, SDS may transport heavy metal, residue of chemicals including plant fertilizer, pesticides and herbicides, dioxins, toxic hydrocarbons, radionuclide contaminants and radioactive isotopes (ibid.).

The fine dust particles, bacteria, pollen and fungi carried by dust storms are reported to have important effects on human health (Péwé, 1981). Suspended materials in the air can be inhaled and cause serious disorders if they accumulate in the respiratory system. Although reporting inconsistent results

across different studies and geographical locations, the literature includes several studies reporting health impacts associated with SDS (e.g. Nativ et al., 1997; Choi et al., 2011; Tam et al., 2012; Baddock et al., 2013; Martinelli, Olivieri and Girelli, 2013; Deroubaix et al., 2013; Sprigg, 2016; Middleton, 2017). Among them, four reviews (de Longueville et al., 2013; Hashizume et al., 2010; Karanasiou et al., 2012; Zhang et al., 2016) have noted similar results, suggesting that potential health effects associated with SDS may increase cardiovascular mortality and respiratory hospital admissions.

Type 2 refers to mental health and well-being effects of SDS that may cause stress, anxiety, depression, grief, sense of loss, strains on social relationship and post-traumatic stress disorder. These kinds of effects are integral parts of the overall SDS-related human health impacts. Although these effects may rarely occur in isolation, they often interact with other socioeconomic and environmental stressors.

Type 3 considers the overall SDS-related impacts on the health of groups and communities. The community health effects can lead to increased interpersonal aggression, increased social instability and decreased community cohesion. The main pathways and types of health impact of SDS are shown in **Figure 18**.



**Figure 18.**  
Major human health impacts of sand and dust storms

The direct impacts on health are mostly caused by changes in exposure to SDS. Communities and individuals differ in their vulnerability to certain health outcomes. A community's health vulnerability is a function of health outcome sensitivity and its capacity to adapt to new conditions. Several factors such as environmental conditions, population size, growth, age, sex, density, food availability, education level, income level, pre-existing health status and the availability and quality of public health care affect a community's health vulnerability.

It is likely that poor populations, and particularly older persons, due to their lower immunological capacity and the very young, due to their not fully developed lungs and airways, are at greatest health risk to SDS. The vulnerability of the poor may endanger the well-being of other members of the same community and hence increase the overall vulnerability of the population.

### 7.4.3. Socioeconomic domain

SDS have profound impacts on socioeconomic systems of different scales, from local up to the global economy. The immediate impacts can be remarkable. China's economic losses due to dust storms and desertification is estimated to amount to US\$ 6.5 billion per year (Youlin, Squires and Qi, 2002).

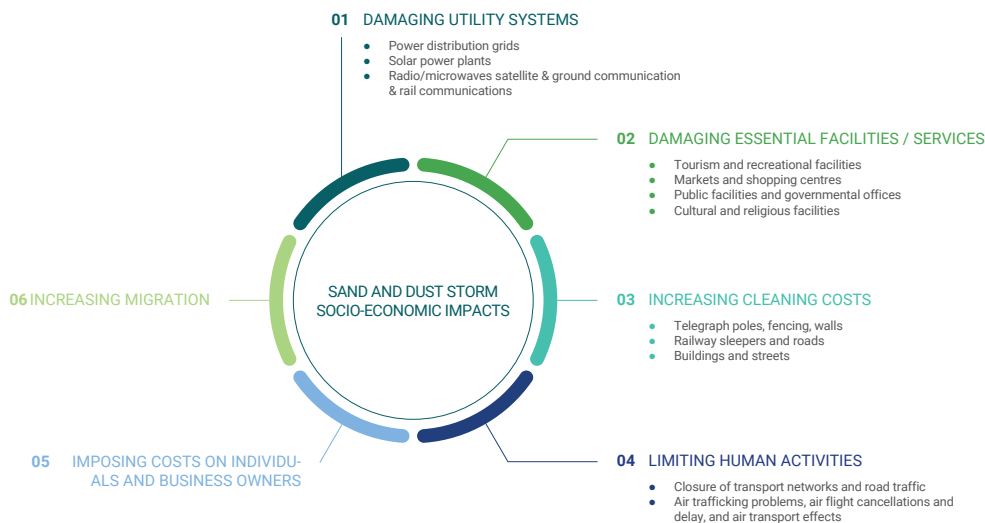
Nonetheless, it is believed that the actual socioeconomic impacts of SDS are difficult to measure because of the long-term consequences and implications they have on the society and economy (United Nations Convention to Combat Desertification [UNCCD], 2016). SDS socioeconomic impacts are more severe as the storms cross populated areas and industrial zones such as big cities and towns. They cause significant harm, both at their sources and through their deposition in downwind areas by reducing air quality and depositing particles (Chan et al., 2005). These impacts encompass a relatively broad range of effects across many sectors of the economy and society.

In general, socioeconomic costs will likely escalate as a result of dust storms (Jeong, 2008; Meibodi et al, 2015). For example, the loss of topsoil, resulting in the loss of soil nutrients, carbon and organic matter, is among on-site costly damages of SDS (Leys, 2002). Sand and dust deposition can harm vegetation by covering them and reducing the photosynthesis process through blocking sunlight or even burying vegetation cover in some areas. Infrastructure can also be sandblasted or buried by SDS. Deposited dust increases cleaning costs, such as for telegraph poles, fencing, walls, railway sleepers and roads (Middleton, 1986; 2017), buildings and streets (Huszar and Piper, 1986). As an example, Huszar and Piper (ibid.) summarized that the major off-site impact of dust storms in the USA was on households, mainly because of cleaning costs of interior spaces and domestic landscapes.

SDS can also cause major damages to utility systems such as power distribution grids (Maliszewski, Larson and Perrings, 2012), solar power plants (Sarver, Al-Qaraghuli and Kazmerski, 2013), radio/microwave satellite and ground communications (Abuhdima and Saleh, 2010) and rail networks (Cheng et al., 2015).

Human activities can be limited, including closure of transport networks and road traffic during SDS (Deetz et al., 2016; Goudie and Middleton, 2006), air trafficking problems (Holyoak, Aitken and Elcock, 2011), flight cancellations and delays (Kang, 2004), and other air transport effects (Tozer and Leys, 2013). SDS can also impose considerable costs on individuals and business owners in both urban and rural areas (Anderson, van Klinken and Shepherd, 2008).

Continued SDS over several years would cause forced migration by destruction of farmlands and facilities (Gregory, 1991). For example, hundreds of thousands of people were forced to leave their homes and migrate because of the Dust Bowl in the 1930s (Hurt, 1981).



**Figure 19.**  
Major socioeconomic impacts of sand and dust storms

Tourism and recreational facilities, markets and shopping centres, public facilities and governmental offices, cultural and religious facilities can also be drastically affected by SDS events. Water resources back-up facilities such as dams, reservoirs, catchments and flood-control installations may be filled up with sand. **Figure 19** depicts the major socioeconomic impact of SDS.

#### 7.4.4. Environment domain

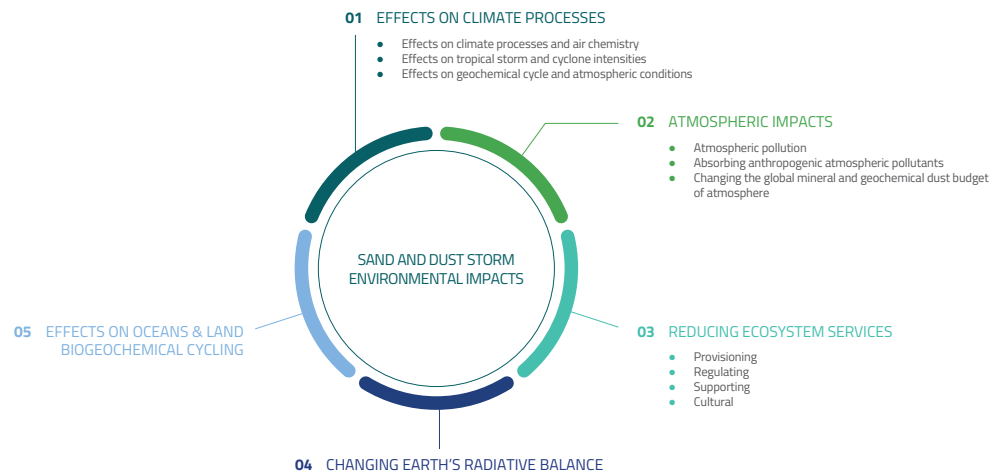
There is significant concern about the impacts of SDS on the environment. SDS have most of their impact within the atmosphere and significantly contribute to atmospheric aerosol loads and pollution (Xie et al., 2005; Xin et al., 2007; Zakey et al., 2006).

The reduction of planetary insolation caused by suspended particles in the atmosphere can have a cooling influence on climate (Seinfeld et al., 2004) and alter Earth's radiative balance (Highwood and Ryder, 2014). This cooling influence, along with varying aerosol loads in the atmosphere, change the atmospheric dynamic structure and modify the atmospheric circulation pattern, with implications for climate change (Shao et al., 2007; Won et al., 2004).

SDS events can impose direct effects on climate processes and air chemistry (Kim et al., 2003), atmospheric geochemical cycles (Shao et al., 2011) and influence oceans and land biogeochemical cycling (Gabric et al., 2010). Dust storms can also have important impacts on tropical storm and cyclone intensities (Evan et al., 2006). SDS transport huge quantities of mineral dust particles from deserts and farmlands and therefore affect the global mineral and geochemical dust budget of atmosphere (Knippertz, 2014; Zender et al., 2004). Moreover, dust particles in the atmosphere can absorb other anthropogenic atmospheric pollutants (Onishi et al., 2012) and transport them to other areas.

Another major impact of SDS on the environment is the reduction of ecosystem services (Lal, 2014) including the four categories: provisioning, regulating, supporting and cultural services. Ecosystem services are contributions of ecosystems to both directly and indirectly support human survival and well-being. Negative impacts on these systems influence the quality of human life. The main environmental impacts of SDS are shown in **Figure 20**.

**Figure 20.**  
**Major**  
**environmental**  
**impacts of sand**  
**and dust storms**



#### 7.4.5. Agroecosystem domain

SDS can have several negative impacts on agroecosystems through soil erodibility, sediment deposition and photosynthesis reduction on agricultural lands (Sivakumar, 2005; Stefanski and Sivakumar, 2009). The worst impact of SDS on agroecosystems is the stripping of topsoil from farmlands that accelerates soil erosion and land degradation and lessens soil productivity (Zobeck, Fryrear and Pettit, 1989).

Topsoil is the most fertile fraction of the soil, made up of minerals and decomposed organic matter that can be removed and transported over long distances. In the long term, SDS can change the nature of soils (Menéndez et al., 2007), as well as their chemical, physical and biological characteristics (Huszar and Piper, 1986). They can also impact contribution of micronutrients to ecosystems (Boy and Wilcke, 2008), cause soil loss (Riksen and De Graaff, 2001) and reduce its water-holding capacity.

A further significant impact of SDS on agroecosystems is through either direct or indirect loss of crop yield and livestock. Direct impacts include physical damage to crops, animals and trees caused by SDS.

Crop yield reduction can be triggered by carrying seeds (Larney et al., 1998), total or partial burial of seedlings under sand and dust deposits, loss of plant leaves as a result of sandblasting and delaying plant development.

Plants exposed to sandblasting (or buried under sand and dust deposits) may lose their leaves, resulting in reduced photosynthetic activity (Sharifi, Gibson and Rundel, 1997) and consequently reduced plant dry matter production that is necessary for plant growth and the development of grain or fruit (Stefanski and Sivakumar, 2009). Direct impacts can be considered in terms of short-term, temporary damage at a particular crop stage (for example, early season, maturity or before harvest) during the growth season to complete crop loss.

SDS may also change the physical and chemical characteristics of a plant's leaves (Farmer, 1993) and reduce plant's biomass (Burkhardt, 2010). Livestock not properly sheltered during the storms could suffer directly (Mu et al., 2013).

For instance, during two dust storms that occurred in China in May 1993 and April 1998, 120,000 and 110,000 livestock were killed, respectively (Shao and Dong, 2006). Environmental stresses caused by SDS can also reduce livestock productivity and growth (Starr, 1988).

SDS can also cause indirect damages such as loss of potential production due to disturbed access to goods and services and increased costs of production. These indirect impacts are the expected result of low incomes, production decline, environmental degradation and other associated factors (Das et al., 2003).

Besides, SDS can increase disease risk of organisms, such as trees, crop plants and animals (Kellogg and Griffin, 2006), threatening food production by affecting rangeland and agricultural productivity (Issanova et al., 2015). They can intensify drought (Han et al., 2008) and even change precipitation regimes (Knippertz and Staut, 2014) and such changes could eventually negatively affect agroecosystems. The major impact of SDS on agroecosystems are shown in **Figure 21**.



**Figure 21.**  
Major impacts  
of sand and  
dust storms on  
agroecosystems



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## 7.5 Identifying indicators for SDS vulnerability mapping

In order to include an indicator in the analysis of SDS-VM, the following questions should be considered:

**Question 1:** How do the given indicators (GIS data layer) contribute to vulnerability to SDS?

**Question 2:** To which vulnerability component(s) (exposure, sensitivity or adaptive capacity) does the given indicator belong?

**Question 3:** To which level of analysis (local, sectoral, national or international) does the given indicator belong?

Answers to these questions will determine whether a particular indicator should be included in the analysis.

**Annex 1** includes the answers to these three questions for each indicator. The potential source of data collection for each indicator is also provided. Alternative web-based data (the majority of which are freely available) are also provided in the tables. Detailed descriptions and web addresses of these sources are given in **Annex 2**.

Where no appropriate data are available, (indicated with "NA"), guidance on how to measure, calculate or extract the given indicator is outlined. Data provided by these sources often vary in scale, quality and content. Therefore, different users must decide which data among all the given sources best suits their needs. The data format of each indicator has also been provided in **Tables 9 to 17** (indicated with "DF" in the tables). However, in some cases, data might be provided in different formats that require conversion.

In summary, the list of the main indicators is provided based on expert assessment and literature review, including all necessary information on data acquisition, data necessity and data sources for SDS-VM. It is then up to the end users at different levels (residential, ecosystem

and political levels) to decide how the associated indicators should be valued and weighted, and how vulnerability should be acted upon.

An ideal SDS-VM would require precise measurements of all the impacts of SDS as input indicators to estimate the vulnerability. However, in practice, several impacts are either not measurable or very difficult to measure. Besides, all the impacts are not equally important; some are only influential under particular circumstances. It is therefore reasonable to restrict them to a set of quantifiable (measurable) indicators.

The relevant indicators for mapping SDS vulnerability are listed in **Tables 9 to 17 (Annex 1)**. Attempts are made to include a large number of indicators associated with SDS vulnerability components, but availability and accessibility of data pose practical limitations on the number finally included in the methodology. These indicators are selected based on the existing literature, experts' knowledge and their contribution to different components of SDS-VM.

The inclusion of some indicators into different components is relatively subjective. Indicators determining the extent and intensity of SDS are assigned to the exposure component. Those indicators reflecting the system's susceptibility to perturbation are included in the sensitivity component. Indicators that are rather more responsive to policy development and prevention strategies are considered as adaptive capacity.

Nevertheless, there are indicators that might be shared among different components. To summarize, this chapter provides an expert assessment of key impacts and indicators to SDS-VM. However, it is then up to the end users at different levels (residential, ecosystem and political) to decide how the associated indicators should be valued and weighted, and how vulnerability should be acted upon.

## 7.6 A geographic information system-based stepwise procedure for SDS vulnerability mapping

### 7.6.1. SDS vulnerability mapping hypothesis

SDS vulnerability mapping can be hypothesized based on the relationship between the system's exposure, its sensitivity and the adaptive capacity. Hence, in order to formulate an appropriate mathematical relationship for vulnerability mapping, extensive literature review and expert consultation is specifically required.

The estimation of SDS-VM components requires measurable indicators which are often affected by a number of limiting factors including data availability and applicability, mapping objectives, precision and accuracy of vulnerability maps, the SDS characteristics (for example, spatial-temporal behaviour, chemical and mineralogical compositions, SDS impacts and the different stages of SDS events (emission, transport and deposition)). Therefore, careful considerations of these factors must be provided in the hypothesis.

### 7.6.2. SDS impact assessment

The SDS vulnerability components have to be measurably expressed in the form of direct and indirect impacts on different scales and in different categories. Therefore, a careful and thorough literature review on impact assessment for directing the SDS vulnerability mapping to measurable indicators is conducted and a wide-ranging and comprehensive methodology for assessing the impacts of SDS is adapted.

Accordingly, four main domains of impacts (human health, socio-economy, environment and agroecosystems) are categorized. These four categories need to be measurably transformable into indicators (for example, GIS layers) for the GIS-SDS-VM. This depends on the

level of economic, social or technological developments, as well as some influential parameters such as distance from SDS sources and physical-chemical characteristics of SDS particles. SDS impacts can vary over different areas and levels, requiring critical care in the SDS impact assessment.

### 7.6.3. Indicator identification

"Indicator identification" describes how to transform assessed impacts of SDS into quantifiable indicators (GIS layers) to which associated variables are categorized. Different stakeholders (users) may choose a set of indicators from those provided in **Annex 1**, depending on their needs, or follow similar criteria and add new indicators to the list.

### 7.6.4. SDS data collection

There do not appear to be specific protocols for required GIS data types, models and structures for a GIS-based SDS-VM. This document mainly focuses on activities to provide basic data requirements for GIS analysis to target the needs of SDS-VM. Data collection is the most expensive activity of any GIS-based analysis, as well as vulnerability mapping. SDS-related data are very heterogeneous, based on their many diverse sources and the data-capturing processes.

Data collection, including primary (direct measurement) and secondary (derived from other data sources) data, is carried out in different spatial scales and for different purposes in both raster and vector data models. Several different sources to collect data on the relevant indicators are provided and alternative sources are listed in **Tables 9 to 17 (Annex 1)**. The same sources might be used for different indicators and afford the user the freedom to select sources for data collection.

### 7.6.5. Data conversion, standardization, storage and management

Data always differ according to certain applications and data acquisition techniques. Data models, for example, vector (point, line, area) and raster (pixel, grid), are two different spatial representations with different advantages and disadvantages to be compared with each other for GIS analysis. Other non-spatial data sources also need to be converted into spatial representations and all data must be transformed into the same data model and structure (for example, map projection, spatial scale and data format).

Unification of different measurement scales (such as nominal, ordinal, interval and ratio) of the indicators is a prerequisite step in GIS analysis. Thus, scaling or standardization must be applied to convert the inconsistent data to unique scale and units. There is a number of methods for standardizing for different purposes (Hwang and Yoon, 2012; Massam, 1988). In the GIS-based SDS-VM, the fuzzy membership functions (Jiang and Eastman, 2000) and the score range procedure (Malczewski, 1999; Malczewski and Rinner, 2015) are more adaptable to standardize the available data.

Different techniques for GIS data storage and management are available to organize spatial and tabular data to be retrievable for updating, querying and analysis. There are several geodatabase management systems applicable for the SDS-GIS-VM. As an example, ARCGIS® geodatabases<sup>1</sup> can be used to store and manage data sets in three levels:

1. File geodatabases: stored as folders in a file system, each data set is held as a file that can scale up to 1 TB in size. The file geodatabase is recommended over personal geodatabases.

2. Personal geodatabases: all data sets are stored within a Microsoft Access data file, which is limited to 2 GB.
3. Enterprise geodatabases: also known as multi-user geodatabases, they can be unlimited in size and numbers of users. Stored in a relational database using Oracle®, Microsoft SQL® Server, IBM DB2®, IBM Informix®, or PostgreSQL®.

### 7.6.6. Weighting of SDS vulnerability mapping elements

Due to the complex nature of the SDS phenomenon and the status of the SDS-VM elements (the components and indicators) with unequal influences, the weighting methodology is a prerequisite for data integration to produce an SDS vulnerability map. Therefore, in order to express the importance of each VM's element relative to others, the weighting functions are required.

A number of methods are developed for weight allocation in different disciplines that are mostly based on ranking from the experts, literature reviews and previous studies (Choo et al., 2012). The GIS-based weightings are mainly carried out in global and local approaches. Global methods assume the spatial homogeneity of measured variables and consequently a single weight will be assigned to each indicator (GIS layer). Ranking, rating and pairwise comparison approaches are common global weighting approaches (Malczewski, 2006).

Unlike global methods, the local approaches allocate weights based on measuring spatial heterogeneity within each indicator (Malczewski and Rinner, 2015). The proximity-adjusted criterion weights, range-based local weighting, and entropy-based local weighting methods are commonly used as local weighting approaches (Malczewski and Rinner, 2015).

1 <http://www.esri.com>, <https://desktop.arcgis.com/en/arcmap/10.3/manage-data/geodatabases/types-of-geodatabases.htm>



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In any scoring/weighting process, the greater the number allocated to an indicator or component, the more that indicator or component will influence the final vulnerability map of the GIS analysis. Although different weighting methods can be used in SDS-VM, the weighting method of the analytic hierarchy process (AHP), a pairwise comparison method introduced by Saaty (1980), is recommended for GIS-based SDS vulnerability mapping, due to its applicability and simplicity in weight allocation.

### 7.6.7. Integration of indicators to produce a map of components

Another critical step in SDS-VM, after selecting indicators of exposure, sensitivity and adaptive capacity and their relative weights, is finding out how to integrate these indicators to construct component maps. Once the weight for each indicator (as well as weights of the components) is obtained, the spatial data integration will be carried out through a raster overlay process to produce exposure, sensitivity and adaptive capacity maps. The component maps are created through Equation 7.1.

$$\text{Component map} = \sum_i^n \text{indicator} * \text{weight}$$

(Equation 7.1)

### 7.6.8. Components map integration to produce SDS vulnerability maps

For the creation of a final vulnerability map, the literature includes three main equations (IPCC, 2012a; UNEP, 2003):

**Vulnerability map=Exposure+Sensitivity - Adaptive Capacity**

(Equation 7.2)

**Vulnerability map=(Exposure\*Sensitivity) /Adaptive Capacity**

(Equation 7.3)

**Vulnerability map= Exposure\*Sensitivity - Adaptive Capacity**

(Equation 7.4)

These equations show profound differences between the ways that the ultimate vulnerability map can be calculated.

Depending on which equation is used for the calculation, the outcome vulnerability map is expected to be inevitably different. Deciding whether adding, multiplying or dividing the indicators should be selected is therefore a significant issue. A practical solution to test the equations is to run the data for a single location, applying each equation and using knowledge from experts' reviews, the results most closely matched reality. This, however, is not a trivial task and requires both knowledge experts and suitable data sets.

In the context of SDS-VM, different components should not be equally considered, since they do not share a linear relationship, as increasing exposure is not linearly linked with the increase in sensitivity. Thus, Equation 7.2 giving equal weights and importance to all the components is not recommended to calculate SDS-VM. Moreover, expressing the SDS-VM equation as a ratio with adaptive capacity as the denominator (as in Equation 7.3) may bias the output vulnerability for marginal values of adaptive capacity. In this case, very low (or high) adaptive capacity will force the vulnerability to be very high (or low). It is hence recommended to create vulnerability maps using Equation 7.4.

## 7.7 Conclusion

Many arid and semi-arid areas worldwide are currently experiencing an increase in the occurrence, distribution and severity of SDS that seem likely to intensify in future. Understanding the expected damage or harm resulting from these events, that is, the level of vulnerability of a society exposed to SDS, is vital, to formulate well-targeted adaptation and mitigation policies and strategies.

Vulnerability is a multidimensional and complex concept, generally expressed as “the capacity to be wounded”. Vulnerability to SDS, as a multi-cause and multi-faceted phenomenon, is contextual and dynamic and encompasses temporal and spatial considerations. It depends on a variety of factors from different domains including health, socio-economy, environment and agroecosystems.

Any vulnerability mapping will necessarily include some assumptions on its three main components of (1) exposure, (2) sensitivity and (3) adaptive capacity. Assumptions can be made in selecting the appropriate indicators to express the components to the measurement and weighting of a given indicator. These assumptions introduce uncertainty into the calculation of each component and will inevitably be aggregated into the ultimate vulnerability map. The inherent complexity and assumptions make any SDS vulnerability mapping methodology subjective, overlapping and contentious to a degree.

Several approaches are available to quantify vulnerability to different environmental hazards. Statistical tools, composite vulnerability indices and GIS-based mapping are among the most prevalent approaches in the literature. This chapter has presented a conceptual GIS-based framework to produce SDS vulnerability map.

Comprehensive consideration is given to the selection of appropriate indicators to measure three vulnerability components based on a careful study of identifying SDS hazardous impacts on different dimensions of human life and the environment. A broad range of indicators are included according to the existing literature, expert’s knowledge and their contribution to different components of SDS vulnerability.

However, data availability and accessibility posed practical limitations to the final number of relevant indicators included.

Major indicators are listed in tables where necessary information on data acquisition, potential data sources, alternative web-based data and relevancy for SDS vulnerability are given. Attempts are made to provide a general methodological framework so that it can easily be adapted by different stakeholders according to their necessities and challenges.

In this sense, end users will decide how to incorporate different indicators and how to value and weight them in the calculation of SDS vulnerability. This guarantees that even with limited data availability and accessibility, a basic map of SDS vulnerability is achievable.

Moreover, a stepwise GIS-based procedure including specific steps required to implement SDS vulnerability mapping is provided to avoid ambiguity for the users. These steps involve a hypothesis, impact assessment, identifying indicators, data collection, data standardization, weighting, indicator integration to produce a component map and finally components map integration to produce an SDS vulnerability map. Each step is elaborated in detail and practical considerations on various procedures are discussed.

This document is the first effort in developing a methodology framework to assess and map SDS vulnerability as no such methodology exists in the literature. The aim was to present an integrated methodology framework to provide a picture of society’s vulnerability to SDS on local to global scales, enabling planners and policy/decision makers to compare the relative overall human vulnerability due to SDS at different levels. The proposed methodology has to be implemented and evaluated through case studies in different sectors, as well as different countries. Further research is required to study driving forces of SDS, its different impacts, indicator identification and three vulnerability components, as illustrated in **Figures 18, 19, 20 and 21**.





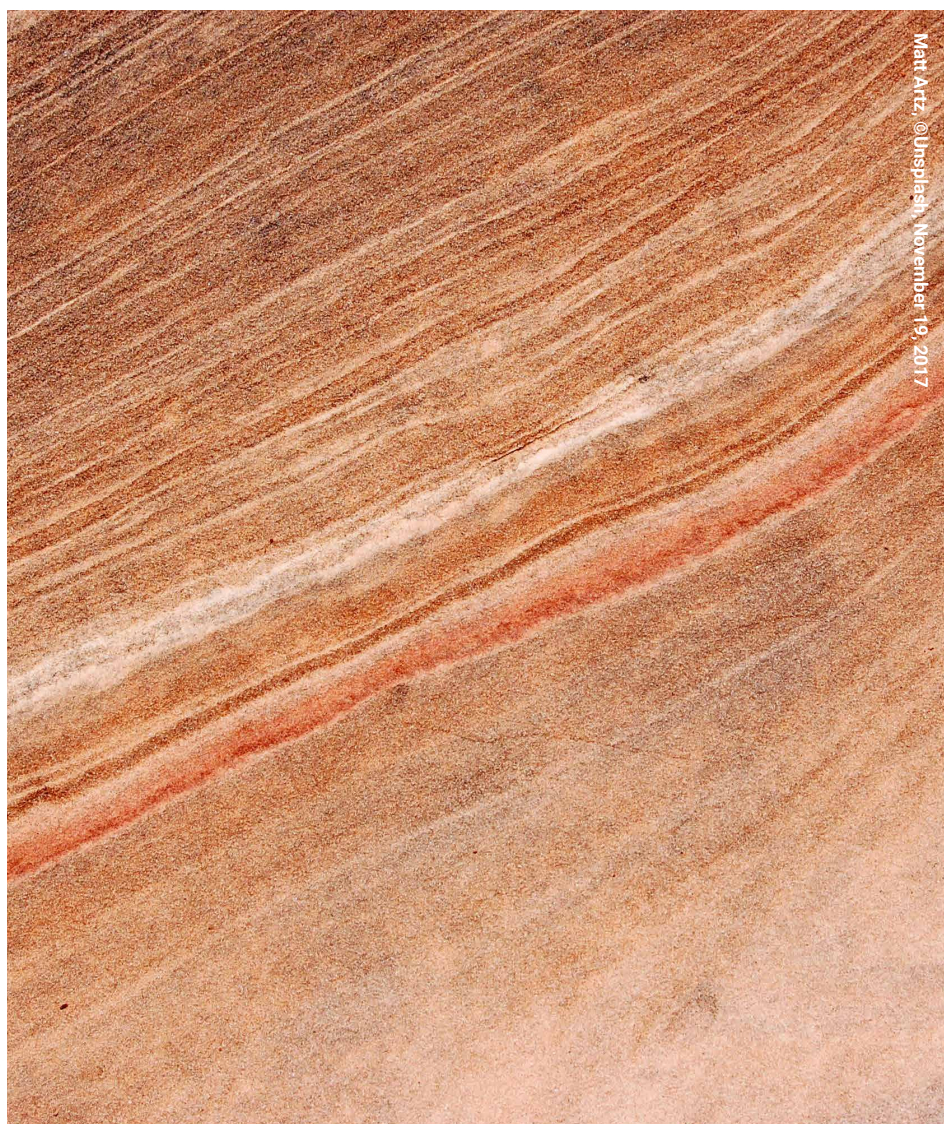
## Annex 1: Potential indicators for SDS vulnerability mapping

Category	Indicator (GIS data layer)	Possible source	Alternative web-based data	Questions (chapter 7.5)
Base maps	Administrative unit (national, provincial/state, city, town, district and village boundaries)  DF: polygon	National map services	DIVA-GIS; Database of Global Administrative Areas (GADM); OpenStreetMap®; Global Land-Use Dataset; Google Maps services; GEONETWORK; Socioeconomic Data and Applications Center (SEDAC) <b>NA:</b> Can be extracted from remotely-sensed imageries and web-based map services.	<b>Q1:</b> Administrative units serve as the basis and starting point for vulnerability mapping, upon which all the other spatial data are based. <b>Q2:</b> – <b>Q3:</b> All levels.
	Elevation, slope and aspect  DF: point/raster	National topographic services	Advanced Spaceborne Thermal Emission and Reflection Radiometer Global Digital Elevation Model (ASTER GDEM); Shuttle Radar Topography Mission (SRTM); Natural Earth; DIVA-GIS; Consultative Group on International Agricultural Research - Consortium for Spatial Information (CGIAR-CSI); GEONETWORK; SEDAC <b>NA:</b> Topographic data can be estimated from satellite (radar, LiDAR and stereo images) data.	<b>Q1:</b> Topographic risk is an integral part of most vulnerability mapping, in particular SDS-VAM. <b>Q2:</b> Exposure. <b>Q3:</b> All levels.
	Land-use/land cover  DF: raster/polygon	National map services	DIVA-GIS; SEDAC; OpenStreetMap; Global Land-Use Dataset; GEONETWORK; United States Geological Survey (USGS) Land Cover; Moderate Resolution Imaging Spectroradiometer (MODIS) products; SEDAC <b>NA:</b> Vegetation maps (forest and agriculture) can replace this layer if no data are available. Such maps can also be estimated from satellite imageries.	<b>Q1:</b> Land cover and/or land-use influence the occurrence, intensity and duration of SDS both at the source and deposition areas. <b>Q2:</b> Sensitivity. <b>Q3:</b> All levels.



**Table 9.**  
**Base data**

Category	Indicator (GIS data layer)	Possible source	Alternative web-based data	Questions (chapter 7.5)
	Watersheds DF: polygon	National statistical services, national hydrological organizations	<a href="#">HydroSHEDS</a> ; GEONETWORK <b>NA:</b> Vegetation maps (forest and agriculture) can replace this layer if no data are available.	<b>Q1:</b> Information on watersheds is important for combating sources of SDS and provides a basis for studies on the scale of basins. <b>Q2:</b> Sensitivity. <b>Q3:</b> Watershed level.



Population distribution map (demographic data)	Age, gender, ethnic groups DF: point/polygon	Census data	World Bank Geodata; SEDAC  <b>NA:</b> Regional and global estimations can be considered.	<b>Q1:</b> Characteristics like age, gender and ethnicity can influence vulnerability. <b>Q2:</b> Sensitivity and adaptive capacity. <b>Q3:</b> All levels.
	Population density DF: point/polygon	Census data	DIVA-GIS; SEDAC; <a href="#">WorldPop</a> ; Global Land-Use Dataset; <a href="#">GEONETWORK</a> ; World Bank Geodata  <b>NA:</b> Regional and global estimates can be considered.	
	Population growth rate DF: point/polygon	Census data	<a href="#">WorldPop</a> ; Atlas of the Biosphere; World Bank Geodata; SEDAC  <b>NA:</b> Regional and global estimates can be considered.	
Socioeconomic and sociopolitical map	Household wealth and income DF: point	Census data	World Bank Geodata; SEDAC  <b>NA:</b> Regional and global estimates can be considered.	<b>Q1:</b> Socioeconomic and sociopolitical circumstances are among the main drivers of adaptive capacity and influence vulnerability. <b>Q2:</b> Sensitivity and adaptive capacity. <b>Q3:</b> All levels.
	Infant mortality rate DF: polygon/point	Census data	SEDAC; World Bank Geodata  <b>NA:</b> Regional and global estimates can be considered.	
	Poverty index DF: polygon/point	Census data	SEDAC; <a href="#">GEONETWORK</a> ; World Bank Geodata <b>NA:</b> Regional and global estimates can be considered.	
	Education level DF: point/polygon	Census data	OpenStreetMap; <a href="#">GEONETWORK</a> <b>NA:</b> Regional and global estimates can be considered.	
	Conflict events/ political violence DF: polygon	National and international reports provided by different organizations	<a href="#">Uppsala Conflict Data Program (UCDP)</a> ; <a href="#">Armed Conflict Location &amp; Event Data Project (ACLED)</a>  <b>NA:</b> Regional and global estimates can be considered.	

**Table 10.**  
**Demographic and socioeconomic data**

**Table 11.**  
**Health and sand**  
**and dust storm**  
**data**

Category	Indicator (GIS data layer)	Possible source	Alternative web-based data	Questions (chapter 7.5)
Health	Health infrastructure index DF: polygon	Census data	<a href="#">GEONETWORK</a> ; World Bank Geodata <b>NA:</b> Regional and global estimates can be considered.	<b>Q1:</b> Health infrastructure index can lower vulnerability by promoting adaptive capacity. <b>Q2:</b> Adaptive capacity. <b>Q3:</b> All levels.
	Emergency response facilities DF: point	National map services; thematic maps	OpenStreetMap <b>NA:</b> Regional and global estimates can be considered.	
	Human health index DF: polygon	Census data	<a href="#">GEONETWORK</a> ; World Bank Geodata <b>NA:</b> Regional and global estimates can be considered.	<b>Q1:</b> Health status is among immediate impacts of SDS and can significantly influence vulnerability. <b>Q2:</b> Sensitivity. <b>Q3:</b> All levels.
	Livestock DF: point	Agriculture census data	GEONETWORK; SEDAC <b>NA:</b> Regional and global estimates can be considered.	
	Wildlife DF: point	Wildlife census data	SEDAC; UN Environment Programme World Conservation Monitoring Centre ( <a href="#">UNEP WCMC</a> ) <b>NA:</b> Regional and global estimates can be considered.	
SDS data	SDS DF: raster	SDS content map; spatial-temporal expansion map; concentration map	MODIS products <b>NA:</b> Can be extracted from satellite data (optical and LiDAR data).	<b>Q1:</b> SDS-related data are used to map vulnerability through exposure component, as the higher the exposure, the higher the vulnerability. <b>Q2:</b> Exposure. <b>Q3:</b> All levels.
	Aerosol optical depth (AOD) DF: raster/point	AOD map; ground stations data	MODIS products; AERONET <b>NA:</b> Can be calculated using a range of satellite data.	
	Visibility DF: raster/point	Meteorological data; Synoptic weather stations data	Calculated from MODIS products and AERONET <b>NA:</b> Can be calculated using AOD data.	
	SDS numerical model outputs (e.g. Weather Research and Forecasting Model (WRF), WRF-Chem and DREAM) DF: raster	Numerical models output data (e.g. World Meteorological Organization Sand and Dust Storm Warning Advisory and Assessment System (WMO-SDS-WAS))	Barcelona Supercomputing Centre <b>NA:</b> Regional dust models.	



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**Table 12.**  
**Meteorological data**

Category	Indicator (GIS data layer)	Possible source	Alternative web-based data	Questions (chapter 7.5)
Meteorological and climate data	Precipitation  DF: raster/point	Meteorological data (stations)	WorldClim; <a href="#">GEONETWORK</a> ; Climate Research Unit (CRU) Climate Datasets; GCM Downscaled Data Portal  <b>NA:</b> Can be derived from remote sensing satellites (e.g. Tropical Rainfall Measuring Mission (TRMM))	<b>Q1:</b> Meteorological factors directly influence SDS formation and spatial-temporal expansion and hence affect vulnerability. <b>Q2:</b> Sensitivity. <b>Q3:</b> All levels.
	Aridity Index	Aridity map	Global Aridity Index  <b>NA:</b> Can be extracted based on meteorological data and remote sensing.	
	Natural disaster hotspots (drought and dust storm)	Disaster hotspot map	Natural Disaster Hotspots  <b>NA:</b> Can be extracted based on meteorological data and remote sensing.	
	Temperature (time series)  DF: raster/point	Meteorological data (stations)	SEDAC; <a href="#">GEONETWORK</a> ; CRU Climate Datasets; GCM Downscaled Data Portal  <b>NA:</b> Can be derived from remote sensing satellites (e.g. MODIS).	
	Wind speed and direction  DF: polyline	Meteorological data (stations)	CRU Climate Datasets; MODIS products; GCM Downscaled Data Portal; Hysplit model; WMO data portal <b>NA:</b> Can be derived from remote sensing satellites (e.g. CALIPSO, CloudSat).	

Category	Indicator (GIS data layer)	Possible source	Alternative web-based data	Questions (chapter 7.5)
	Air pressure DF: raster/polyline	Meteorological data (stations)	CRU Climate Datasets; GCM Downscaled Data Portal <b>NA:</b> Can be derived from remote sensing satellites (e.g. CALIPSO, CloudSat).	
	Albedo DF: raster	Reflectance data	NASA Earth Observations (NEO); MODIS products <b>NA:</b> Can be retrieved from remote sensing satellites (e.g. Landsat, Sentinel).	<b>Q1:</b> Shows the ability of the surface to reflect solar light, has a significant impact on soil moisture and regulates meteorological variables. <b>Q2:</b> Exposure. <b>Q3:</b> All levels.

Category	Indicator (GIS data layer)	Potential source	Alternative web-based data	Questions (chapter 7.5)
Transport	Railway DF: polyline	National map services, organizational thematic maps	SEDAC; OpenRailwayMap <b>NA:</b> Can be extracted from remotely-sensed imageries and web-based map services.	<b>Q1:</b> Communication routes and networks are vulnerable and will be affected by SDS through accidents and cancellations. On the other hand, they can help people to communicate for better adaptation and mitigation. <b>Q2:</b> Sensitivity and adaptive capacity. <b>Q3:</b> All levels, mainly sectoral.
	Road DF: polyline	National map services, organizational thematic maps	OpenStreetMap; SEDAC; gROADS <b>NA:</b> Can be extracted from remotely-sensed imageries and web-based map services.	



**Table 13.**  
**Transport and utility network**

Category	Indicator (GIS data layer)	Potential source	Alternative web-based data	Questions (chapter 7.5)
	Airline routes DF: polyline	IATA airline map and national airway maps	OpenFlights <b>NA:</b> --	
	Marine DF: polyline	National map services and organizational thematic maps	World Port Index <b>NA:</b> Can be extracted from remotely-sensed imageries and web-based map services.	<b>Q1:</b> These infrastructures will experience the reduction of their desired efficiency as SDS is increased. <b>Q2:</b> Sensitivity and adaptive capacity. <b>Q3:</b> All levels, mainly sectoral.
	Airport, harbours, bus terminals, train stations DF: point	National map services and organizational thematic maps	OpenStreetMap; OpenFlights; World Port Index <b>NA:</b> Can be extracted from remotely-sensed imageries and web-based map services.	
Utility network and facilities	Communication stations, electricity and gas stations	National map services and organizational thematic maps	OpenStreetMap; <a href="#">GEONETWORK</a> <b>NA:</b> Can be extracted from remotely-sensed imageries and web-based map services. (e.g. Google Maps services, Bing maps).	<b>Q1:</b> Utility networks will be negatively affected by SDS and influence vulnerability. <b>Q2:</b> Sensitivity. <b>Q3:</b> Local and sectoral.
	Power plants, electric power facilities and distribution lines	National map services and organizational thematic maps	OpenStreetMap; <a href="#">GEONETWORK</a> <b>NA:</b> Can be extracted from remotely-sensed imageries and web-based map services. (e.g. Google Maps services, Bing maps).	
	Telecommunication facilities and distribution lines (cables, networks)	National map services and organizational thematic maps	OpenStreetMap; <a href="#">GEONETWORK</a> <b>NA:</b> Can be extracted from remotely-sensed imageries and web-based map services. (e.g. Google Maps services, Bing maps).	

Category	Indicator (GIS data layer)	Possible source	Alternative web-based data	Questions (chapter 7.5)
Essential facilities	Tourism and recreational facilities DF: point/polygon	National map services and organizational thematic maps	OpenStreetMap; <a href="#">GEONETWORK</a> <b>NA:</b> Can be extracted from remotely-sensed imageries and web-based map services. (e.g. Google Maps services, Bing maps).	<b>Q1:</b> They will be negatively affected by SDS and influence vulnerability. <b>Q2:</b> Sensitivity. <b>Q3:</b> Local and sectoral.
	Cultural and religious facilities DF: point/polygon	National map services and organizational thematic maps	OpenStreetMap; <a href="#">GEONETWORK</a> ; United Nations Educational, Scientific and Cultural Organization (UNESCO) reports <b>NA:</b> Can be extracted from remotely-sensed imageries and web-based map services. (e.g. Google Maps services, Bing maps).	<b>Q1:</b> They provide essential facilities for adaptation and mitigation to SDS. <b>Q2:</b> Adaptive capacity. <b>Q3:</b> Up to national level.
	Public facilities and governmental offices DF: point/polygon	National map services and organizational thematic maps	OpenStreetMap; <a href="#">GEONETWORK</a> <b>NA:</b> Can be extracted from remotely-sensed imageries and web-based map services. (e.g. Google Maps services, Bing maps).	
	Markets and shopping centres DF: point/polygon	National map services and organizational thematic maps	OpenStreetMap; <a href="#">GEONETWORK</a> <b>NA:</b> Can be extracted from remotely-sensed imageries and web-based map services. (e.g. Google Maps services, Bing maps).	
Industrial facilities	Factories DF: point	National map services and organizational thematic maps	OpenStreetMap; <a href="#">GEONETWORK</a> <b>NA:</b> Can be extracted from remotely-sensed imageries and web-based map services. (e.g. Google Maps services, Bing maps).	<b>Q1:</b> As SDS frequency increases, the industrial sector will experience the reduction of the labour-force efficiency, reducing product quality and increasing costs of cleaning. <b>Q2:</b> Sensitivity. <b>Q3:</b> All levels, mainly sectoral.
	Food industry DF: point	National map services and organizational thematic maps	OpenStreetMap; <a href="#">GEONETWORK</a> <b>NA:</b> Can be extracted from remotely-sensed imageries and web-based map services. (e.g. Google Maps services, Bing maps).	

**Table 14.**  
**Industrial facilities**

**Table 15.  
Vegetation  
data**

Category	Indicator (GIS data layer)	Possible source	Alternative web-based data	Questions (chapter 7.5)
Vegetation	Agriculture DF: raster/ polygon	National map services, cadastral and land-use maps	OpenStreetMap; SEDAC; <a href="#">EarthStat</a> ; GIAM; Global Land-Use Dataset  <b>NA:</b> Can be extracted from remotely-sensed imageries (e.g. Landsat and Sentinel).	<b>Q1:</b> Distinguish the different types of agro-economic activities which are sensitive to dust particles. They also have positive roles in reducing vulnerability by increasing adaptive capacity from the viewpoint of local community's economy. <b>Q2:</b> Sensitivity and adaptive capacity. <b>Q3:</b> All levels, mainly sectoral.
	Horticulture and orchard DF: raster/ polygon	National map services, cadastral and land-use map	OpenStreetMap; SEDAC; <a href="#">EarthStat</a> ; GIAM; USGS Land Cover  <b>NA:</b> Can be extracted from remotely-sensed imageries (e.g. Landsat and Sentinel).	
	Rangeland DF: raster/ polygon	National map services, natural resources and land cover map	Global Land-Use Dataset; SEDAC; USGS Land Cover  <b>NA:</b> Can be extracted from remotely-sensed imageries (e.g. Landsat and Sentinel).	<b>Q1:</b> Distinguish the different types of green coverage which are sensitive to dust particles. They also have positive roles in reducing vulnerability by absorbing suspended particles. <b>Q2:</b> Sensitivity. <b>Q3:</b> All levels.
	Forest DF: raster/ polygon	National map services, natural resource maps	Atlas of the Biosphere; <a href="#">GEONETWORK</a> ; <a href="#">UNEP WCMC</a> ; <a href="#">USGS Land Cover</a> ; Phased Array type L-band Synthetic Aperture Radar (PALSAR) forest/non-forest map, MODIS products  <b>NA:</b> Can be extracted from remotely-sensed imageries (e.g. Landsat and Sentinel).	

Category	Indicator (GIS data layer)	Possible source	Alternative web-based data	Questions (chapter 7.5)
Water	Lakes, dams and water reservoirs DF: polygon	National map services, hydrological maps, organizational thematic maps	SEDAC; OpenStreetMap; Global Reservoir and Dam Database ( <a href="#">GRanD</a> ); <a href="#">Global Lakes and Wetlands Database (GLWD)</a>  <b>NA:</b> Can be extracted from remotely-sensed imageries (e.g. MODIS and Landsat).	<b>Q1:</b> Distinguish the surface water bodies that need protection against dust pollutants deposition. In addition, they play a positive role in air humidity, wet deposition and air cooling. <b>Q2:</b> Sensitivity. <b>Q3:</b> All levels.
	Rivers and drainage network and canals DF: polyline	National map services, hydrological maps, organizational thematic maps	HydroSHEDS  <b>NA:</b> Can be extracted based on topographic data (e.g. SRTM).	
	Wetlands DF: raster/polygon	National map services	<a href="#">UNEP WCMC</a> ; <a href="#">GLWD</a> <b>NA:</b> Can be extracted from remotely-sensed imageries (e.g. MODIS and Landsat).	<b>Q1:</b> Distinguish the different wetland ecosystems and the exposed flora and fauna. They have positive impacts on air humidity, wet deposition and air cooling. <b>Q2:</b> Sensitivity. <b>Q3:</b> All levels.
	Groundwater level DF: raster/polygon	Groundwater maps	Global groundwater maps  <b>NA:</b> Can be extracted from remotely-sensed imageries (e.g. GRACE).	<b>Q1:</b> The lower the groundwater level, the more vulnerable the land for SDS emission and the higher the vulnerability. <b>Q2:</b> Sensitivity. <b>Q3:</b> All levels.
Snow cover map	Average snow depth and snow cover DF: polygon/raster	Snow depth and snow cover maps	Atlas of the Biosphere; MODIS products  <b>NA:</b> Can be extracted from remotely-sensed imageries (e.g. Landsat and Sentinel)	<b>Q1:</b> Snow depth and snow cover have impacts on vulnerability by absorbing SDS pollutant particles. <b>Q2:</b> Sensitivity. <b>Q3:</b> All levels.



**Table 16.**  
**Water and precipitation**

**Table 17.  
Soil and  
geomorphology**

Category	Indicator (GIS data layer)	Possible source	Alternative web-based data	Questions (chapter 7.5)
Soil	Soil erodibility DF: raster/ polygon	Soil erodibility map	<a href="#">GEONETWORK</a> ; Atlas of the Biosphere; FAO soil maps;  <b>NA:</b> can be calculated by soil erosion models (e.g. European Soil Erosion Model (EUROSEM))	<b>Q1:</b> The higher the soil erodibility, the higher the vulnerability to SDS. <b>Q2:</b> Sensitivity. <b>Q3:</b> All levels.
	Soil moisture DF: raster/ polygon	Soil moisture maps	Satellite-derived products such as Soil Moisture and Ocean Salinity (SMOS) and Soil Moisture Active Passive (SMAP) satellite maps  <b>NA:</b> Can be extracted from remotely-sensed imageries.	<b>Q1:</b> Soil moisture and texture affect soil sensitivity to erosion and influence vulnerability. <b>Q2:</b> Sensitivity. <b>Q3:</b> All levels.
	Soil texture DF: raster/ polygon	Soil physical properties maps	<a href="#">GEONETWORK</a> ; <a href="#">World Soil Information</a> ; FAO soil maps  <b>NA:</b> Can be extracted from remotely-sensed imageries.	
	Forest DF: raster/ polygon	National map services, natural resource maps	Atlas of the Biosphere; <a href="#">GEONETWORK</a> ; <a href="#">UNEP WCMC</a> ; <a href="#">USGS Land Cover</a> ; PALSAR Forest/Non-Forest map, MODIS products  <b>NA:</b> Can be extracted from remotely-sensed imageries (e.g. Landsat and Sentinel).	
Geology and Geomorphology	Geological maps DF: raster/ polygon	National map services, organizational thematic maps	<a href="#">GEONETWORK</a> ; OneGeology Portal  <b>NA:</b> Can be extracted from remotely-sensed imageries.	<b>Q1:</b> Provide information for SDS-VAM by contributing to soil erodibility map generation. <b>Q2:</b> Sensitivity. <b>Q3:</b> All levels.
	Geomorphology and Landforms DF: raster/ polygon	National map services, organizational thematic maps	OneGeology Portal  <b>NA:</b> Can be extracted from GIS modelling by remotely-sensed imageries.	

Note: NA: No appropriate data are available.  
DF: Data format.

## Annex 2: Data available on the web

**ACLED** (<http://www.acleddata.com/data>) is a database that codes the dates and locations of all reported political violence and protest events in over 60 developing countries. Political violence includes events that occur within civil wars and periods of instability.

**AERONET** (<https://aeronet.gsfc.nasa.gov/>) provides globally distributed observations of spectral aerosol optical depth (AOD), inversion products and perceptible water in diverse aerosol regimes.

**ASTER GDEM** (<https://asterweb.jpl.nasa.gov/gdem.asp>) provide 30m resolution global elevation data derived from ASTER satellite images. ASTER GDEM coverage spans from 83 degrees north latitude to 83 degrees south, encompassing 99 per cent of Earth's landmass.

**Atlas of the Biosphere** (<https://nelson.wisc.edu/sage/data-and-models/atlas/>) provides information about the environment and human interactions with the environment including per capita oil usage, literacy rate, population growth rate, cropland and built-up land, soil pH, snow depth, snow coverage and more.

**Barcelona Supercomputing Centre** (<https://ess.bsc.es/bsc-dust-daily-forecast>) demonstrates the ongoing value of climate services, air quality services and dust services to society and the economy.

**CGIAR-CSI** (<http://srtm.csi.cgiar.org/>) is a geoportal that provides Shuttle Radar Topographic Mission (SRTM) 90m (and resampled 250m) digital elevation data (DEM) for the entire world. The SRTM DEM are originally produced by NASA and are considered among the most valuable elevation data worldwide.

**CRU Climate Datasets** (<http://www.cru.uea.ac.uk/data/>) provides a variety of available high- and low- resolution data sets including precipitation, temperature, pressure, drought.

**DIVA-GIS** (<http://www.diva-gis.org/gdata/>) contains a collection of spatial data worldwide, including administrative areas, inland water, roads, railways, elevation, land cover, population and climate. Spatial data have been collected from different sources and are available for any country in the world.

**EarthStat** (<http://www.earthstat.org/>) provides geographic data sets of the distribution of particular crops, water depletion and natural vegetation, among other data sets.

**GADM** (<http://www.gadm.org/>) is a spatial database of the location of the world's administrative boundaries including countries and lower level subdivisions.

**GCM Downscaled Data Portal** (<http://www.ccafs-climate.org/data/>) includes a wide range downscaled (higher-resolution) data created from the outputs of a wide range of global climate models. It contains the majority of important climate variables with a better spatial resolution.

**GEONETWORK** (<http://www.fao.org/geonetwork/srv/en/main.home>) A geographic information system (GIS) aggregation website including administrative and political boundaries, agriculture and livestock, applied ecology, base maps, remote sensing, biological and ecological resources, watersheds (river basins), climate, fisheries and aquaculture, forestry, human health, hydrology and water resources, infrastructures, land cover and land-use, population and socioeconomic indicators, soils and soil resources and topography.

**GIAM** (<http://waterdata.iwmi.org/>) contains information on global irrigated and rain-fed croplands, irrigation water sources (surface, groundwater), cropping intensity (single, double, continuous) and dominant crop types.

**Global Aridity Index** (<https://cgiarcsi.community/data/global-aridity-and-pet-database/>) provides global indices of aridity data and at 30 arc-second resolution in raster format.

**Global groundwater maps** ([https://www.whymap.org/whymap/EN/Maps\\_Data/maps\\_data\\_node\\_en.html](https://www.whymap.org/whymap/EN/Maps_Data/maps_data_node_en.html)) is a spatial portal to provide data and information about the major groundwater resources of the world.

**Global Lakes and Wetlands Database (GLWD)** (<https://www.worldwildlife.org/pages/global-lakes-and-wetlands-database>) is a portal including global maps of lakes, reservoirs, wetlands, swamps, and other environments.

**Global Land Use Dataset** (<http://nelson.wisc.edu/sage/data-and-models/global-land-use/grid.php>) includes a number of data sets showing population, land area, cropland area, land cover, land suitability for cultivation, grazing land area and built-up area at 0.5 degree resolution.

**Global Reservoir and Dam (GRaND) Database** (<http://atlas.gwsp.org/index.php>) is an online data set that compiles reservoirs with a storage capacity of more than 0.1 km<sup>3</sup>. The data includes spatially explicit records of dams and reservoirs at high spatial resolution with extensive metadata.

**Global Roads Open Access Data Set (gROADS)** (<http://sedac.ciesin.columbia.edu/data/set/groads-global-roads-open-access-v1/data-download>) is a data set of roads worldwide hosted by the Center

- for International Earth Science Information Network (CIESIN).
- HydroSHEDS** (<https://www.hydrosheds.org/>) contains hydrological data and maps extracted from the Shuttle Radar Topography Mission (STRM) elevation data including global river networks, watershed boundaries, drainage directions and flow accumulations.
- MODIS products** (<https://modis.gsfc.nasa.gov/data/dataproduct/>) provides a rich data set of global atmosphere, land, cryosphere and ocean products. A great number of products are included, for instance, snow cover, aerosol products, cloud product, land cover, albedo and many more.
- NASA Earth Observations (NEO)** ([https://neo.sci.gsfc.nasa.gov/view.php?datasetId=MCD43C3\\_M\\_BSA](https://neo.sci.gsfc.nasa.gov/view.php?datasetId=MCD43C3_M_BSA)) provides Albedo data retrieved from satellite imageries.
- Natural Disaster Hotspots** (<http://sedac.ciesin.columbia.edu/data/collection/ndh#>) is a geportal including a range of geographic data on natural disasters (including volcanoes, earthquakes, landslide, flood and 'multihazards') with hazard frequency and economic loss, among other indicators.
- Natural Earth** (<http://www.naturalearthdata.com/>) provides a convenient resource for making custom maps. It contains free vector and raster map data at 1:10m, 1:50m, and 1:110m scales. The data includes country borders, administrative maps, populated places, urban areas, water bodies and boundaries, islands, coastline, glaciated areas, land cover and shaded relief. Bear in mind that some data are only available for particular countries/continents.
- OneGeology Portal** (<http://portal.onegeology.org/OnegeologyGlobal/>) is a spatial portal including combined geological data from many geological organizations across the world. Basic geological data are available for many countries.
- OpenFlights** (<https://openflights.org/data.html>) contains airports, airline routes, train stations and ferry terminals spanning the globe.
- OpenRailwayMap** (<http://www.openrailwaymap.org/>) is a detailed online map of global railway infrastructure, built on OpenStreetMap data.
- OpenSeaMap** ([http://openseamap.org/index.php?id=openseamap&no\\_cache=1](http://openseamap.org/index.php?id=openseamap&no_cache=1)) provides online map of global marine ways, built on OpenStreetMap data.
- OpenStreetMap** (<http://www.geofabrik.de/data/download.html>) is a crowdsourced database including a number of GIS-ready shapefiles such as urban extent, administrative boundaries, roads, points of interest, buildings and ferry routes.
- PALSAR Forest/Non-Forest map** ([http://www.eorc.jaxa.jp/ALOS/en/palsar\\_fnf/fnf\\_index.htm](http://www.eorc.jaxa.jp/ALOS/en/palsar_fnf/fnf_index.htm)) Global 25m resolution PALSAR-2/PALSAR Mosaic and Forest/Non-forest map of a freely available dataset generated by applying Japan Aerospace Exploration Agency (JAXA)'s powerful processing and sophisticated analysis method/techniques to several images obtained with Japanese Phased Array type L-band Synthetic Aperture Radars (PALSAR and PALSAR-2) on Advanced Land Observing Satellite (ALOS) and Advanced Land Observing Satellite-2 (ALOS-2).
- Protected Planet** (<https://www.protectedplanet.net/>) is a publicly available online platform where terrestrial and marine protected areas and access-related statistics can be explored and downloaded.
- Socioeconomic Data and Applications Center (SEDAC)** (<http://sedac.ciesin.columbia.edu/>) is a data centre in NASA's Earth Observing System Data and Information System (EOSDIS) hosted by CIESIN at Columbia University. It provides a range of socioeconomic spatial data, including settlement points, urban areas, environmental indicators (annual maps of PM<sub>2.5</sub>, urban heat islands, land surface temperature, NO<sub>2</sub> concentrations), spatial economic data, population density, population, global anthropogenic biomes, roads, agricultural lands, water bodies, poverty maps (for 28 countries) and many more regional and local data (log in required).
- UNEP GEOdata** (<http://geodata.grid.unep.ch/>) is the authoritative source for data sets used by United Nations Environment Programme (UNEP) and its partners in the Global Environment Outlook (GEO) report and other integrated environment assessments. Its online database holds more than 500 different variables, as national, subregional, regional and global statistics or as geospatial data sets (maps), covering themes like fresh water, population, forests, emissions, climate, disasters, health and GDP.
- UNEP WCMC** (<http://datadownload.unep-wcmc.org/datasets>) includes a wide range of data sets from the United Nations Environment Programme (UNEP) World Conservation Monitoring Centre such as global wetlands, global distribution of coral reefs, mangrove distributions, tropical dry forests, wilderness, global distribution of saltmarshes and more.
- Uppsala Conflict Data Program (UCDP)** (<http://ucdp.uu.se/>) is an online map presenting the location and statistics of instances of political violence in different parts of the world.
- USGS Land Cover** (<https://www.usgs.gov/core-science-systems/science-analytics-and-synthesis/gap/science/land-cover-data-download?qt-science>)

[center\\_objects=0#qt-science\\_center\\_objects](#)) is a very useful web page providing a great number of links to many land cover, forestry, albedo, agriculture, river observations and many more data sets.

**WMO GAWSIS** (<https://gawsis.meteoswiss.ch/GAWSIS/#/>). The World Meteorological Organization (WMO) Global Atmosphere Watch Station Information System.

**WMO OSCAR** (<https://www.wmo-sat.info/oscar/>). The Observing Systems Capability Analysis and Review Tool (OSCAR) is the WMO's official repository of WIGOS metadata for all surface-based observing stations and platforms.

**WMO SDS-WAS** (<https://sds-was.aemet.es/>) and ([https://www.wmo.int/pages/prog/arep/wwrp/new/Sand\\_and\\_Dust\\_Storm.html](https://www.wmo.int/pages/prog/arep/wwrp/new/Sand_and_Dust_Storm.html)). WMO Sand and Dust Storm Warning Advisory and Assessment System.

**WMO WIGOS** ([https://www.wmo.int/pages/prog/www/wigos/index\\_en.html](https://www.wmo.int/pages/prog/www/wigos/index_en.html)). WMO Integrated Global Observing System.

**World Bank Geodata** (<http://databank.worldbank.org/data/home.aspx>) includes a wide range of global data such as population, financial data, education statistics and indicators, gender statistics, health nutrition and population statistics and many more data sets.

**World Port Index** ([http://msi.nga.mil/NGAPortal/MSI.portal?\\_nfpb=true&\\_pageLabel=msi\\_portal\\_page\\_62&pubCode=0015](http://msi.nga.mil/NGAPortal/MSI.portal?_nfpb=true&_pageLabel=msi_portal_page_62&pubCode=0015)) is a database that contains the location and physical characteristics of, and the facilities and services offered by, major ports and terminals worldwide.

**World Soil Information** (<https://www.isric.org/>) is a geoportal that provides soil information on national and/or local levels. Gridded datasets covering the world's soils at a maximum resolution of 5 arc-minutes with 22 attributes for each cell including organic carbon content, clay content, silt content, sand content and water capacity.

**WorldClim** (<http://www.worldclim.org/>) is a set of global climate data (temperature (min, max, mean) and precipitation) with a spatial resolution of about 1 km<sup>2</sup>. Climate data are available from the past, present and predicted data for future conditions.

**WorldPop** (<http://www.worldpop.org.uk/>) is an open access database of high spatial resolution, contemporary data on human population distributions for most parts of the world.

## 7.8 References

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