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# Drought Risk Assessment and Management

## - A Conceptual Framework -

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*River Rhine, August 2018 (Source: Pixabay)*

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## Abstract

In the context of global warming, droughts are increasingly threatening our societies. They last for months or even years, affecting wide areas and large numbers of people, with single drought events sometimes causing economic damages for several billion Euros. Besides the economic damages, droughts can compromise ecosystems and threat food security in the most vulnerable countries.

To reduce drought impacts, drought risk assessments need to be implemented in order to support policy makers and water managers in developing coping strategies and drought management plans. Due to the wide-ranging direct and indirect, often cascading impacts, drought risk assessments need to include information tailored to specific sectors and oriented to the needs of specific users.

**Drought risk** as defined here is the likelihood to incur damages and economic losses during and after a drought and depends on the interactions between three dimensions:

1) the **severity** and the **probability** of occurrence of a certain **drought event**,

2) the **exposed assets and/or people**, and

3) their intrinsic **vulnerability** or **capacity to cope** with the hazard.

The characterization of these dimensions and the representation of their interactions over different socio-economic sectors poses several challenges. This document discusses these challenges and proposes a theoretical framework to assess drought risk at global scale in order to provide policy relevant information. Based on the described conceptual approach, the JRC developed the Global Drought Observatory (GDO) as a first operational dynamic drought risk monitor for the entire globe.

The report is structured as follows:

Firstly, the causes and characteristics of drought events as well as their link with climate variability and climate change are discussed (chapters 1 and 2).

Secondly, the concept of drought risk is presented, including a first approach to map drought risk at global scale as a function of hazard, exposure and vulnerability (chapter 3). This framework is then linked to expected impacts in different economic sectors and the environment, including the discussion of case studies from Argentina, South Africa, Syria and the United States (chapter 4).

Finally, a brief introduction to the key aspects of drought risk management and an outlook on future challenges and opportunities are presented in chapters 5 and 6.

# 1 Introduction

Among the weather-related natural disasters drought is likely the most complex and severe due to its intrinsic nature and wide-ranging and cascading impacts that affect, among others, agricultural production, public water supply, energy production, transportation, tourism, human health, biodiversity and natural ecosystems. Droughts are recurrent, can last from a few weeks to several years, and affect large areas and populations around the globe every year. The related impacts develop slowly, are non-structural, often indirect and can linger for long times after the end of the drought itself. While the impacts result in severe economic losses, environmental damage and human suffering, they are in general less visible than impacts of other natural hazards (e.g. floods, storms) that cause immediate and structural damages, which are clearly linked to the hazard and quantifiable in economic terms (UNISDR, 2011). The drought risk, therefore, is often underestimated. While the need for a pro-active drought risk management has been recognized, its implementation is still lagging behind.

Drought-related fatalities mainly occur in poor economies, especially when regions are also involved in social unrest or military conflicts. However, also in wealthy countries people suffer from indirect effects such as heat stress or dust, leading to a variety of health impacts (e.g. van Lanen et al., 2017; WMO and GWP, 2014). Economic and social consequences can range far beyond the immediately impacted areas. Examples are persistent unemployment, migration and social instability related to failures in public water supply and food insecurity (WWAP, 2016).

Under a changing climate, drought is likely to become more frequent and severe in the 21st century in many regions of the world (Spinoni et al., 2018a & 2018b; IPCC, 2014). A better understanding of the drought phenomenon, especially of the physical processes leading to drought, its propagation through the hydrological cycle, the societal and environmental vulnerability to drought and its wide-ranging impacts are more important than ever. The key challenge is to move from a re-active society fighting impacts to a pro-active society that is resilient and adapted to the drought risk, i.e. adoption of proactive risk management strategies (WMO and GWP, 2014; Wilhite et al., 2014). This includes, among other aspects, the analysis of the evolving drought hazard and the related impacts (past trends and future projections), as well as the analysis of the societal and environmental exposure and vulnerability. All together determine the drought risk, which can be managed by developing drought policies and drought management plans that are adapted to the regional, national and local context (WMO and GWP, 2014; GWP CEE, 2015).

The goal of this report is to discuss the various aspects that determine and characterise droughts (chapter 1); to highlight the influence of climate variability and climate change (chapter 2); to illustrate the concept of drought risk, including a first approach to map drought risk at global level (chapter 3); to list the impacts to be expected in different economic sectors and the environment, including the discussion of a few case studies (chapter 4); to provide a short introduction to the key aspects of drought risk management (chapter 5); and, finally, to give an outlook on future challenges and opportunities (chapter 6).

## 1.1 What is a Drought?

The term drought is widely used but no unique definition exists across disciplines. A consequence is the difficulty to understand drought characteristics across time and space. In general terms, IPCC (2012) defined drought as "a period of abnormally dry weather long enough to cause a serious hydrological imbalance". It results from a shortfall of precipitation over a certain period of time and/or from a negative water balance due to an increased atmospheric water demand following high temperatures or strong winds. This situation may be exacerbated by antecedent conditions in soil moisture, reservoirs and aquifers, for example, and typically lasts from months to a few years. Extreme "Megadroughts" can persist for decades, while so-called "Flash Droughts" are short periods (< 3 months) of high temperatures, resulting in a fast depletion of soil moisture that can lead to major impacts (Mo and Lettenmaier, 2016).

Indeed, droughts are a recurring feature of all climates and are defined with respect to the long-term average climate of a given region (e.g., Heim Jr., 2002; Dai, 2013). They are to be distinguished from aridity, a seasonally or fully dry climate (e.g., desert) and from water scarcity, a situation where the climatologically available water resources are insufficient to satisfy long-term average water requirements (e.g. van Lanen et al. 2017; Tallaksen and van Lanen, 2004).

Depending on the prevailing effects on the hydrological system and the resulting impacts on society and environment, meteorological, soil moisture, and hydrological droughts (groundwater, streamflow, reservoirs) are distinguished (Box 1). The definition of a drought and the assessment of the related risk, therefore, will depend on the sector analysed and the related processes and impacts.

***Box 1: Drought types***

Depending on the effect in the hydrological cycle and the impacts on society and environment, different drought types are commonly distinguished:

(1) *Meteorological drought* is a period of months to years with a deficit in precipitation or climatological water balance (i.e. precipitation minus potential evapotranspiration) over a given region. The deficit is defined with respect to the long-term climatology. A meteorological drought is often accompanied by above-normal temperatures and precedes and causes other types of droughts. Meteorological drought is caused by persistent anomalies in large-scale atmospheric circulation patterns, which are often triggered by anomalous tropical sea surface temperatures (SSTs) or other remote conditions. Local feedbacks such as reduced evaporation and humidity associated with dry soils and high temperatures often enhance the atmospheric anomalies (Trenberth, 1988).

(2) *Soil Moisture (agricultural) drought* is a period with reduced soil moisture that results from below-average precipitation, less frequent rain events, or above-normal evaporation.

(3) *Hydrological drought* occurs when river stream flow and water storages in aquifers, lakes, or reservoirs fall below long-term mean levels. Hydrological drought develops more slowly because it involves stored water that is depleted but not replenished. Time-series of these variables are used to analyse the occurrence, duration and severity of hydrological droughts.

The large variety of drought impacts point to a multitude of drivers that turn lower than average precipitation, limited soil moisture and low water levels into disasters for vulnerable communities and economies (UNISDR, 2011). Therefore, drought risk not only depends on the characteristics of the physical hazard (intensity, duration, severity), but also on the exposed assets (e.g., crops, people, water intensive industries, natural ecosystems) and the vulnerability of the affected society and ecosystems. A shortage of precipitation during the growing season, for example, leads to reduced soil moisture and impinges on crop production or ecosystem function in general (soil moisture drought, also termed agricultural drought); during the runoff and percolation season, it primarily affects water supplies (hydrological drought).

While a lack of precipitation often triggers drought, other factors, including more intense but less frequent precipitation, poor water management, and soil erosion, can also cause or enhance these droughts. Overgrazing, for example, led to elevated erosion and dust storms that amplified the "Dust Bowl" drought of the 1930s over the Great Plains in North America (Cook et al. 2009).

## 1.2 Drought Indicators

Droughts are monitored and quantified by sector oriented drought indicators, typically derived from hydro-climatic variables like precipitation, climatic water balance, soil moisture, river flow, and groundwater. In addition, related impacts, such as reductions in greenness or vegetation vigour are often used indicators.

Most commonly, drought indicators are presented in the form of standardised indices used to analyse droughts in different domains of the water cycle. Drought indicators are usually designed either for drought monitoring and awareness raising or for water management (Beguería et al., 2014). However, they are also useful for drought forecasting (Dutra et al., 2014; Sheffield et al., 2014), climate change studies (Trenberth et al., 2014; Dai et al., 2018), and as input for drought impact modelling (Zampieri et al., 2017) and drought risk assessments (Svoboda, 2015).

Different drought types require different indicators for their characterisation. The Standardized Precipitation Index (SPI, McKee et al., 1993) and the Standardized Precipitation-Evapotranspiration Index (SPEI, Vicente-Serrano et al., 2010), for example, are well known for meteorological drought analysis. Soil moisture-related indicators such as the Soil Moisture-based Drought Severity Index (Cammalleri et al., 2016) or the Palmer Drought Severity Index (Palmer, 1965) aim to characterise drought impacts in terms of plant water stress. Hydrological indicators, such as flow percentiles are used to quantify the volume of water deficit in rivers and reservoirs (Hisdal et al., 2004; Cammalleri et al., 2017). Finally, remote sensing-based indicators such the Normalized-Difference Vegetation Index (NDVI) or the fraction of Absorbed Photosynthetically Active Radiation (fAPAR) are used to monitor drought impacts on the vegetation cover.

More recently, combined indicators that blend several physical indicators into a single indicator were developed. The European Drought Observatory, for instance, uses the Combined Drought Indicator (CDI, Sepulcre-Canto et al., 2012) to monitor drought impacts on agricultural and natural ecosystems. The World Meteorological Organisation and the Global Water Partnership (WMO and GWP, 2016) published a recent overview on widely used drought indicators.

To obtain an overview of the potential impacts of droughts, a set of variables is needed in order to represent different aspects related to the water deficit. Among the key drought variables are frequency, severity (sometimes also called magnitude), intensity and duration (Table 1). Severity describes the accumulated deficit over the entire duration of an event, while intensity describes the average degree of the precipitation, soil moisture, or water storage deficit during a drought. Both may include consideration of the associated impacts. As depicted in Table 1, the duration and area affected are linked to the propagation in time and space of the water deficit. Longer and more widespread events might thus trigger cascading effects, the magnitude of which is directly related to the water deficit. The timing of the onset, cessation and end of a drought are particularly relevant information during the growing season. It is worth noting that the impacts of a drought may be felt after the drought has ended, as measured by the reference indicator.

***Table 1***. Main variables to characterise drought events.

| Variable | Description | Relevance |
|---|---|---|
| **Frequency** | Number of drought events per defined time interval | More frequent droughts can cause long-term impacts on affected ecosystem |
| **Severity** (Magnitude) | Related to the water deficit. Computed as the sum of the differences, in absolute values, between the drought indicator (DI) values and the threshold used to define the level of dryness. $S_i = \Sigma \|DI_i\| < \text{Threshold}$ | Deficit of water in relation to the water needed for specific uses (e.g. irrigation, domestic water consumption, energy production, etc.) |
| **Intensity** | Severity divided by duration of the event. | Characterizes the overall potential for impacts |
| **Duration** | Number of days, months or time steps of the event. | Longer droughts propagate further through the hydrological cycle with a higher potential for cascading and secondary effects |
| **Onset** | First day, month or time step for which the indicator is below a given threshold. | Relevant if a drought starts in sensitive periods with greater water demand like seeding and flowering periods. Relevant for drought management and the declaration of farming emergencies |
| **Cessation** | Meteorological indices have returned to normal, soil moisture is restoring, pasture growth re-establishes, forest growth re-establishes, reservoirs and lakes refill. | Relevant for management |
| **End-point** | Agricultural and natural ecosystem productivity returns to average pre-drought conditions, Lake and reservoir levels return to average pre-drought conditions. Socio-economic conditions return or stabilize to normal conditions. | Relevant for management |
| **Peak month** | Day or month with the lowest value of the drought indicator. | Period with the potentially strongest impact |
| **Area affected** | Area or percentage of a region (or country) with values of the drought indicator below a certain threshold. | The wider the area, the more exposed assets are affected |

# 2 Climate Variability, Climate Change and Drought Hazard

## 2.1 Past Droughts

Drought is a normal part of climate variations. Tree-ring and other proxy data, together with instrumental records, have revealed that large-scale droughts have occurred many times during the past millennium in many parts of the world (Dai, 2011a; Glaser, 2001).

Examples illustrate that prehistoric and early historic societies were highly vulnerable to climatic disturbances. Many lines of evidence now point to climate forcing as the primary agent in repeated social collapse (Weiss and Bradley, 2001). In northern coastal Peru, for example, the Moche civilization suffered a ~30 year drought in the late 6$^{th}$ century AD accompanied by severe flooding. The capital city was destroyed, surrounding fields and irrigation systems were swept away and widespread famines ensued. The capital was subsequently transferred northward and new adaptive agricultural and architectural technologies were implemented (Shimada et al. 1991). Four hundred years later, the agricultural base of the Tiwanaku civilization of the central Andes collapsed as a result of a prolonged drought period documented in ice and lake sediment cores (Kolata et al., 2000). In Mesoamerica, lake sediment cores show that the Classic Maya collapse of the 9$^{th}$ century AD coincided with the most severe and prolonged drought of that millennium (Brenner et al., 2001). In North America, Anasazi agriculture could not sustain three decades of exceptional drought and reduced temperatures in the 13$^{th}$ century AD, resulting in forced regional abandonment (Dean et al. 1993). Dai (2011a) and Cook et al. (2015) demonstrated that large-scale megadroughts occurred in northern America and Europe in the first half of the second millennium. The North American droughts in the 1930s and 1950s, including the well-known Dust Bowl, had similar intensity but shorter durations. Among the likely causes of such intense and persistent droughts are ENSO-related Sea-Surface Temperature patterns in the tropical Pacific Ocean and land surface feedbacks, for example due to land degradation (Cook et al. 2009).

Nowadays and on a global scale, warming of the lower atmosphere strengthens the hydrologic cycle, mainly because warmer air can hold more water vapour (Coumou and Rahmstorf, 2012; Trenberth, 2010). This strengthening causes dry regions to become drier and wet regions to become wetter, something that is also predicted by climate models (Trenberth, 2010). Warming leads to more evaporation and evapotranspiration, which enhances surface drying and, thereby, the intensity and duration of droughts (Trenberth, 2010). Aridity increase since the 1950s and 1970s, respectively, has been estimated between 0.50 to 1.74 percent per decade, but natural cycles have played a role as well (Cherlet et al., 2018; Dai, 2011a; Dai 2011b). Dai (2013) further reports that warming induced drying has increased the areas under drought by about 8 percent since the 1980s.

Figure 1 shows the results of an analysis of the global change in meteorological drought severity between the periods 1951-1980 and 1981-2010, using the Standardized Precipitation Index (SPI; McKee et al., 1993; Guttman, 1999) and the Standardized Precipitation-Evapotranspiration Index (SPEI, Vicente-Serrano et al., 2010; Begueria et al., 2014). Meteorological drought can be due to a prolonged precipitation deficit (Mishra and Singh, 2010) as represented by the SPI or the combined effect of a precipitation deficit and a high evaporative demand (Dai et al., 2018), as represented by the SPEI.

Top panels in Figure 1 show the cumulative severity of all drought events during the period 1981-2010. Computations are based on observed data from Global Precipitation Climatology Centre dataset (GPCCv7; Becker et al., 2013) and from the University of East Anglia's Climate Research Unit (CRUTSv4.01; Harris et al., 2014) at medium-high spatial resolution (0.5°). Bottom panels show the difference in drought severity between 1981-2010 and 1951-1980. Cold and desert areas are masked due to limited meaning of drought in these areas.

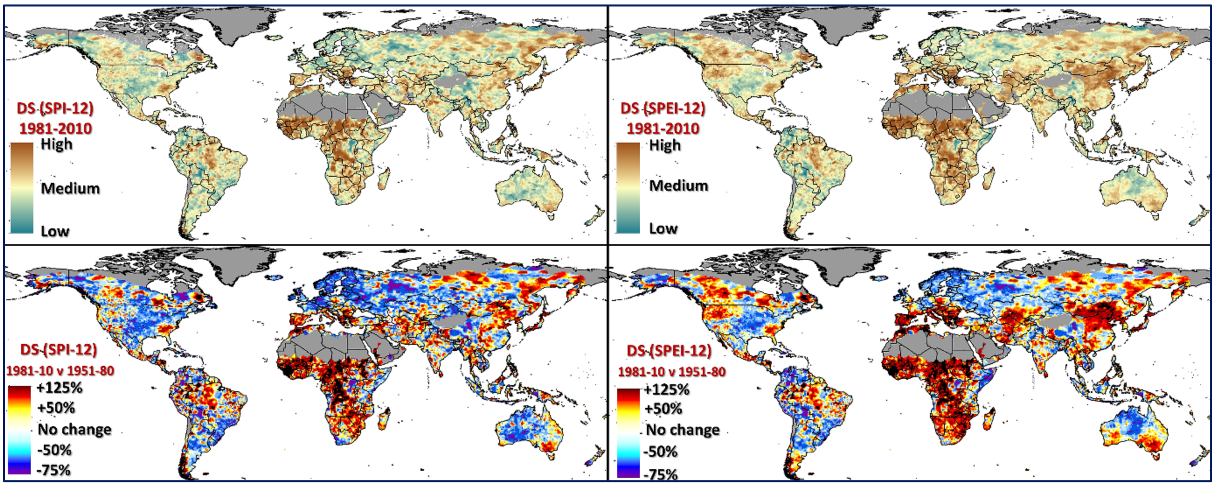



***Figure 1.*** *Drought severity according to the SPI-12 (left) and the SPEI-12 (right). Top panels show the cumulative severity for the period 1981-10, bottom panels show the difference between the periods 1951-80 and 1981-2010. Grey zones represent masked cold and desert areas.*

Though the values (and the differences between periods) are larger according to the SPEI-12, which includes the effects of rising temperatures, both indicators agree on the meteorological drought hotspots of the recent decades: the Amazon Forest, the Mediterranean region, most of Africa, northeastern China, and southeastern Australia. The areas at the borders between northwestern United States and southwestern Canada are a hotspot only for the SPEI-12.

## 2.2 Sub-seasonal to Seasonal Variability and ENSO

Droughts are caused by changes in persistent atmospheric circulation patterns usually connected to slowly varying atmospheric boundary conditions (i.e. changes in sea surface temperature, sea ice cover, land-atmosphere interactions). Together with other low frequency sources (like the Madden Julian Oscillation, the North Atlantic Oscillation), the El Niño-Southern Oscillation (ENSO) proved to be one of the main sources of episodic droughts around the world (Trenberth et al., 2014; Davey et al. 2014). Natural cycles of ocean - atmosphere interaction lead to recurring swings between anomalously warm (El Niño) and cold (La Niña) sea surface temperature states in the equatorial Pacific. During an ENSO event, drought can occur virtually anywhere in the world, although researchers have found the strongest connections between ENSO and intense drought in Australia, India, Indonesia, the Philippines, Brazil, parts of east and south Africa, the western Pacific basin islands (including Hawaii), Central America, and various parts of the United States. Drought occurs in each of the above regions at different times (seasons) during a warm or cold event and in varying degrees of magnitude. For instance, the date of the monsoon onset in tropical Australia is generally 2–6 weeks later during El Niño years than in La Niña years.

An emerging consideration in drought analysis is the occurrence of subseasonal (< 3 months) drought events that can serve to intensify or extend longer-term drought or background aridity. These "flash droughts" refer to relatively short periods of warm surface temperature and anomalously low and rapidly decreasing soil moisture. Based on the physical mechanisms associated with flash droughts, these events are classified into two categories: heat wave and precipitation deficits (Otkin et al., 2017).

In 2012, the areal extent of drought in the United States jumped from 30 to over 60% within the three months from May to July. Large precipitation deficits combined with record-high temperatures and abundant sunshine led to very rapid drought development across the central United States. This means that locations that generally had near-normal conditions at the end of May had fallen into extreme drought conditions only two to three months later. This flash drought had a substantial impact with losses estimated to be in excess of US$30 billion across the entire nation. Similarly, in 2016, extreme drought conditions rapidly developed during the fall across a large portion of the southeastern United States, with an extensive area experiencing up to a four-category increase in drought severity over a three-month period. Across the northern high plains in 2017, warm and exceptionally dry weather during the spring and early summer led to up to a four-category increase in drought severity over a two-month period.

The monitoring and forecasting of drought is undergoing a paradigm shift with regard to the treatment of evapotranspiration (ET), evaporative demand ($E_0$), and the consideration of temperature impacts on drought in a changing climate. Remotely sensed actual ET is also a complement to drought indices based on potential ET such as the evaporative demand drought index (EDDI) (Hobbins et al., 2016; Roderick et al., 2015), which describes the desiccating power of the local atmospheric conditions. High evaporative demand can be an effective early indicator of rapid drought onset, although it does not always result in actual drought impacts materialising on the ground, for example due to an amelioration by ancillary moisture sources. Forecasts of $E_0$ at timescales ranging from daily to seasonal are increasingly desired by stakeholders and managers in a number of sectors, including agriculture, water-resource management, and wildland-fire management, largely driven by recent developments highlighting the value of $E_0$ for drought monitoring. However, few such $E_0$ forecasting tools currently exist.

Further, multi-year and decadal trend assessments are unreliable without base periods long enough to capture natural variability.  Major uncertainties surround the degree to which ENSO, the Pacific Decadal Oscillation, and the Interdecadal Pacific Oscillation are and will be affected by climate change and their effects on long-term evapotranspiration (Wood et al., 2015).

Understanding the mechanisms behind low frequency climate features like ENSO is key to improve our capabilities for a timely seasonal prediction of drought events. Even if it is still incipient, reliable seasonal prediction together with a reliable monitoring network and an appropriate risk assessment will allow for the development of early warning systems and the timely implementation of drought relief assistance (Dutra et al., 2014; Naumann et al., 2014).

## 2.3 Climate Change and Future Droughts

Improvements in knowledge have reinforced the findings of the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC), especially with respect to an increasing risk of rapid, abrupt, and irreversible change with high levels of warming. These risks include increasing aridity, drought and extreme temperatures in many regions of the world (World Bank Group, 2012). Despite the uncertainty in climate projections, several regions of the globe are likely to experience increased drought frequencies and/or intensities in the 21$^{st}$ century, among them the Mediterranean, Southern Africa, and Central America (Orlowsky and Seneviratne, 2013).

A reduction in precipitation or changing precipitation patterns as well as greater evaporative demands related with higher temperatures are the underlying processes driving such changes. A temperature increase of 3°C would bring current 100-year droughts (severe droughts that currently only occur once every 100 years) to around 30% of the emerged lands on a 10-yearly basis (Naumann et al., 2018a).

These scenarios suggest that drought risk will increase for many economic sectors and vulnerable regions unless appropriate climate change mitigation and adaptation measures are taken. Many regions in the world with high population densities and vulnerable societies that rely on local agricultural production could experience significant losses because of droughts. These regions remain a high priority for better-targeted impact monitoring and quantification as a basis for drought management and adaptation. The recent climate change, characterized in particular by rising temperatures at global level, has many consequences; one of the most discussed is the increased frequency of weather-related extreme events (IPCC, 2014). Drought is no exception and, in the last decades, a general tendency towards more frequent and extreme droughts has been discussed and reported in the scientific literature (Sheffield et al., 2012; Dai, 2013).

Post-AR4 studies indicate that there is medium confidence in a projected increase in duration and intensity of droughts in some regions of the world, including Southern Europe and the Mediterranean region, central Europe, central North America, Central America and Mexico, northeast Brazil, and Southern Africa. Elsewhere there is overall low confidence because of insufficient agreement of projections of drought changes, dependent both on model and dryness index (Seneviratne et al., 2012). While mean precipitation will increase in a warmer world (virtually certain), precipitation tends to decrease in subtropical latitudes, particularly in the Mediterranean. Precipitation changes generally become statistically significant only when temperature rises by at least 1.4°C, and in many regions the projected changes during the 21$^{st}$ century lie within the range of late 20$^{th}$ century natural variability (Mahlstein et al. 2012). Less precipitation will fall as snow and snow cover will decrease in extent and duration (high confidence), and dry regions and seasons become drier (high confidence). It is important to recognize that model-simulated changes in the incidence of meteorological (rainfall) droughts vary widely, so that there is at best medium confidence in projections (Seneviratne et al., 2012).

Changes in evaporation have spatial patterns similar to those of changes in precipitation, with very likely increases in a warmer climate, thereby accelerating the hydrologic cycle. Decreases in soil moisture are likely in several regions, particularly in central and southern Europe, and southern Africa (medium to high confidence). For a range of scenarios, soil moisture droughts lasting 4 to 6 months double in extent and frequency, and droughts longer than 12 months become three times more common, between the mid-20$^{th}$ century and the end of the 21$^{st}$ century (Sheffield and Wood, 2008). A decrease in soil moisture can at the same time increase the risk of extreme hot days and heat waves (Seneviratne et al., 2006).

Since future projections frequently suffer from uncertainties (Dai and Zhao, 2017; Zhao and Dai, 2017; Moon et al., 2018, Naumann et al., 2018a), the following figures are based on the largest possible combination of simulations as input data, i.e. precipitation and temperature data from 109 simulations from the Coordinated Regional Downscaling Experiment (CORDEX; http://www.cordex.org/). They demonstrate the results for two different climate scenarios: the moderate emission scenario RCP4.5 (Thomson et al., 2011) and the more extreme scenario RCP8.5 (Riahi et al., 2011).

Compared to the analysis of past trends (Figure 1), the effect of temperature becomes more evident in drought projections (Figure 2). According to the SPI-12, the drought severity is likely to increase in limited areas by the end of 21$^{st}$ century: Chile and Argentina, the Mediterranean, and large parts of southern Africa, under both climate scenarios. Sparse areas in south-eastern China and in southern Australia are likely to experience an increase in drought severity only under the more extreme climate scenario, the RCP8.5. It is also interesting to highlight that latitudes above 45°N show a widespread decrease in drought severity as the 21$^{st}$ century progresses. Instead, the SPEI-12 suggests that many more regions will likely experience more frequent and severe drought events: As expected, almost the entire globe, excluding Alaska, northern latitudes in Eurasia, and maritime South-East Asia, show a tendency towards an increase in drought severity, which is even stronger according to the RCP8.5.

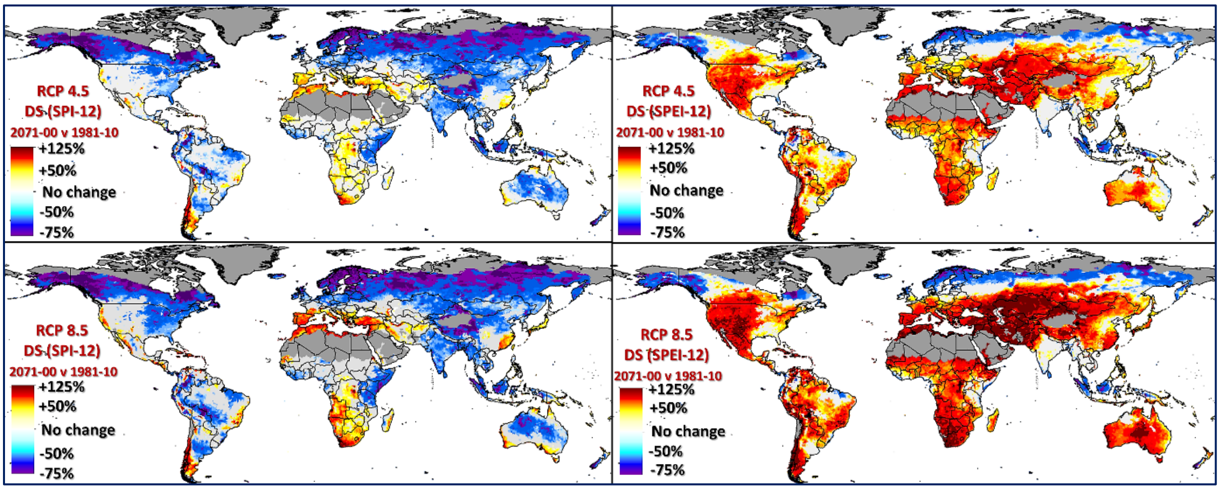



***Figure 2.*** *Drought severity (DS) according to the SPI-12 (left) and the SPEI-12 (right). All panels show the difference in percentage between 1981-2010 and 2071-2100 under the RCP4.5 (top) and the RCP8.5 (bottom) scenarios. Light grey zones represent areas in which less than two thirds of the simulations agree on the sign of change. Dark grey zones represent the cold and desert masked areas.*

Combining the information derived from Figures 1 and 2, we notice that most of the drought hotspots of the last decades are projected to see a further increase in drought severity, thus becoming the areas at highest risk of drought impacts or even irreversible land degradation processes. The regions that show a continuous increase in drought severity from 1951 to 2100, according to both indicators analysed and under both future scenarios are southern Chile and Argentina, the Mediterranean region, and large parts of southern Africa. In the mentioned areas, the temperature effect is likely to exacerbate droughts, but the drying trend is the most important climate driver for meteorological droughts in these areas. On the other hand, over North America, the Amazon rainforest, sub-Saharan Africa, central Asia, and Australia, the rising temperatures are likely to play the key role in meteorological drought trends.

As we notice from Figure 3, over the three mentioned hotspots drought severity is projected to increase in most of the areas, especially under the RCP8.5 scenario. In particular, close to 100% of the Mediterranean is likely to experience increasing drought severity under this scenario according to both the SPI-12 and the SPEI-12, thus the shift towards drier and hotter climates can have dramatic consequences in southern Europe. The same is valid over areas at latitudes below 10°S in Africa. Over the third hotspot region, i.e. Chile and Argentina, the drying trend is limited to Chile and the southernmost parts of Argentina, whilst in the plains located in central Argentina, a wetting trend projects less severe droughts as the 21$^{st}$ century progresses.

At global scale (see Figure 4), drought severity increased from 1951-1980 to 1981-2010 over more than half of the land area (excluding Antarctica and the masked cold and desert zones) according to both the SPI and the SPEI (slightly larger). By the end of the century, drought severity is likely to increase for over approximately 14% (under RCP4.5) and 16% (under RCP8.5) of the land areas, according to the SPI-12. When the effect of increasing atmospheric demand is considered (i.e. analysing SPEI-12) these values rise to approximately 67% (under RCP4.5) and to 73% (under RCP8.5).

Oppositely, land areas that present a decrease in drought severity due to changes in precipitation (SPI-12) range between 33% and 35%, depending on the RCP scenario, whilst only about the 17% to 22% of the land areas will show a decrease, if the atmospheric demand is taken into account (SPEI-12). Finally, many areas in the world still show high levels of uncertainty due to differences in the climate simulations.

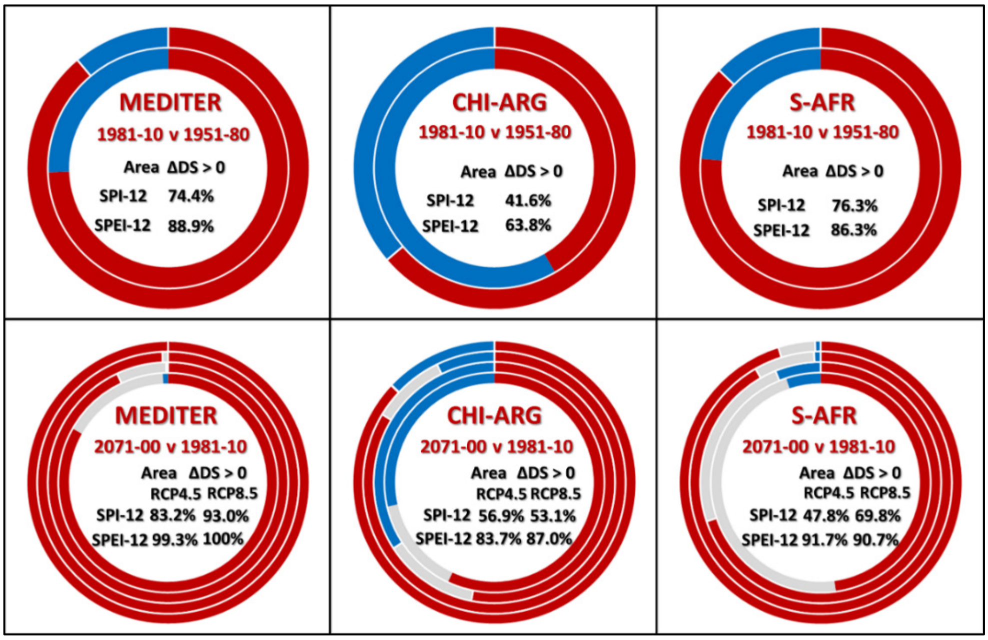



***Figure 3.*** *Percentage of areas in which drought severity increased from 1951-1980 to 1981-2010 (top) and from 1981-2010 to 2071-2100 (bottom) in three hotspot areas: Mediterranean (MEDITER), southern Chile and Argentina (CHI-ARG), and southern Africa (S-AFR). Red indicates an increase in drought severity, blue a decrease, grey stands for uncertain projected change. In the top panels, the inner circle refers to the SPI-12 and the outer to the SPEI-12. In the bottom panels, from inside to outside circles: SPI-12 RCP4.5, SPI-12 RCP8.5, SPEI-12 RCP4.5, and SPEI-12 RCP8.5.*

Figure 4 shows in light grey the areas in which more than one third of the simulations disagree regarding the sign of the projected changes. These transition areas vary according to different indicators and scenarios. Overall, such "uncertain" areas represent approximately 51% for both RCPs according to the SPI-12 and approximately 10% under both RCPs according to the SPEI-12. This suggests that climate simulations tend to show a higher level of agreement in drought projections if changes in temperature are taken into account, also because of the structure of climate models (Taylor et al., 2012). On the other hand, meteorological drought projections based only on precipitation result more often in uncertain tendencies, thus they may be improved using the planned next generation of climate models (Eyring et al., 2016).

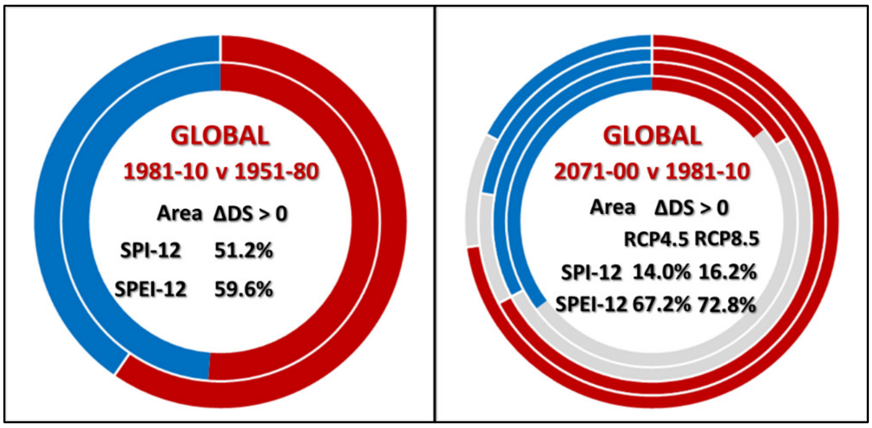



***Figure 4.*** *Percentage of areas in which drought severity increased from 1951-80 to 1981-10 (left) and is projected to increase from 1981-10 to 2071-00 (right). For explanations, see Figure 3 and text.*

# 3 Assessing Global Drought Risk

## 3.1 Concept

The term "risk" and the related terms of "hazard", "exposure" and "vulnerability" have been used and defined in different ways within the scientific community, with notable differences between the Disaster Risk Reduction (DRR) and the Climate Change Adaptation (CCA) communities (Brooks, 2003). They base their analysis on two theoretical frameworks, commonly referred to as the **outcome or impact approach** (CCA community) and the **contextual or factor approach** (DRR community) (Tánago et al. 2016, Naumann et al. 2018b).

The outcome or impact approach is based on the relationships between stressor and response. Here the endpoint of the analysis is the vulnerability (the more damage a society suffers, the more vulnerable it is). This approach relies on the use of quantitative measures of historical impacts as proxies for the vulnerability estimation (Brooks et al., 2005, Peduzzi, 2009). However, relying on historical impacts has several limitations, mainly because impact data are often unavailable or available for short timescales only, which inhibits the derivation of homogenous global risk maps. In addition, the number of affected people and the types of impacts vary by region, thus hindering consistent broad-scale analyses.

The contextual or factor approach is based on intrinsic social or economic factors that define the vulnerability. Here the vulnerability is the starting point, allowing understanding why the exposed population or assets are susceptible to the damaging effects of a drought. It is more suitable for setting targets for disaster risk reduction. This approach generally relies on combined indicators, which are mathematical combinations of risk determinants that have no common unit of measurement (OECD-JRC, 2008). The resulting values are not an absolute measure of economic loss or damage to the society or the environment, but a relative statistic that provides a regional ranking of potential impacts, which can serve to prioritize actions for reinforcing disaster management and adaptation plans.

Both approaches represent alternative but complementary ways for drought risk estimation at different scales and coordination levels. Since drought impacts are context specific and vary geographically, regression models (i.e. outcome approach) are important for developing preparedness plans and mitigation activities from local to national scales, while composite indicators (i.e. contextual approach) can identify generic leverage points for reducing impacts at the regional to global scales.

For the presented global assessment, we adopt the contextual approach, which defines risk as a function of the natural hazard, the exposed assets and the inherent vulnerability of the exposed social or natural system:

$$Risk = f\ (Hazard,\ Exposure,\ Vulnerability)$$

where vulnerability is defined as an inherent property of a system that exists independently of the external hazard (Brooks, 2003, p.4).

Following this definition, the **risk** to incur **damages and economic losses from a drought** depends on the combination of the **severity** and the **probability of occurrence** of a certain event, the **exposed assets and/or people**, and their intrinsic **vulnerability** or capacity to cope with the hazard. Table 2 summarises the main characteristics of the three components of drought risk as well as relevant data needed to represent them.

*__Table 2.__ Components of drought risk analysis. Adapted from van Lanen et al. (2017)*

| Component | Characterization | Data |
|---|---|---|
| **Hazard** | Magnitude of a hydro-meteorological deficit | Meteorological, hydrological and/or biophysical indicators |
| **Exposure** | Amount of elements and assets subject to a drought hazard | Quantity and location of human population, infrastructure, economic activities and/or ecosystems |
| **Vulnerability** | Sensitivity of exposed elements to damaging effects of droughts | Composite indicators that include social, economic, environmental and/or infrastructural components |
| **Overall risk** | Potential damages and losses from droughts to a specific asset | Measured in a probabilistic scale as a combination of the drought magnitude or severity, level of exposure and vulnerability. Linked to intervention policies and management plans |

End users, water managers and policy makers rely on drought risk assessments for better protecting population from shocks and for developing management plans to reduce drought impacts. Drought risk assessments, therefore, should include information tailored to the needs of specific users. This information should answer the questions on where and which entities are more likely to be affected, and why they are sensible to drought events. Since exposure and vulnerability vary between economic sectors (e.g. agriculture, public water supply, energy production, inland water transport, tourism, public health) and different ecosystems, drought risk assessments need to be sector specific.

## 3.2 Assessing the Risk for Agriculture and Other Primary Sectors

In this section, we present an **example** of a **global drought risk assessment** with emphasis on agricultural and primary sector impacts, which are important at the global scale. The assessment is based on the conceptual approach proposed by the United Nations Development Programme (UNDP/BCPR, 2004) and applied by Carrão et al. (2016). It includes the assessment of the hazard, the exposure, and the societal vulnerability, which are then combined to arrive at an assessment of the risk for significant impacts due to droughts. The individual steps are explained in the following subsections.

### 3.2.1 Assessing the hazard

Precipitation can be considered as a proxy indicator of the water available to the coupled human–environment system (Svoboda et al., 2002). The frequency and intensity of abnormal precipitation deficits, therefore, can represent the drought hazard for a given area.

In the present assessment, **drought hazard** is estimated as the probability of exceedance of the median of global severe precipitation deficits for a historical reference period (1901-2010) (Figure 6, top left panel). The severity of the precipitation deficit is computed by means of the Weighted Anomaly of Standardized Precipitation (WASP) index (Lyon and Barnston, 2005). The WASP-index was selected since it is standardized in time and space; allows confining the influence of large standardized anomalies that result from small precipitation amounts occurring during the dry seasons; and it emphasizes anomalies during the heart of the rainy season when, for instance crops are more sensitive to water fluctuations.

### 3.2.2 Assessing the exposure

Meaningful information on the **exposure** is related to the entities, assets, infrastructures, and people located in a drought prone area. The model of drought exposure as applied here is computed and validated on the basis of spatially explicit geographic layers. As defined in Carrão et al. (2016) this approach to drought exposure is comprehensive and takes into account the spatial distribution of several physical elements (proxy indicators) characterizing agriculture and primary sector activities, namely: crop areas (agricultural drought), livestock (agricultural drought), industrial/domestic water stress (hydrological drought), and human population (socioeconomic drought) (Box 2).

***Box 2: Exposure layers***

**Gridded population data** were retrieved from the Global Human Settlement Layer (GHSL, 1 km resolution) and used to account for the spatial distribution of population exposed to droughts. The GHSL population estimates correspond to the residential population for 2015 (EC, 2015). Population was consistently disaggregated from census or administrative units to grid cells, informed by the distribution and density of built-up areas as mapped in the GHSL global layer.

**Agricultural lands** are based on the Global Agricultural Lands in the Year 2000 dataset. This data set represents the proportion of land area used as cropland in the year 2000. Satellite data from MODIS and SPOT-VEGETATION were combined with agricultural inventory data to create this product on a 5 min x 5 min latitude-longitude resolution. This indicator represents the extent and intensity of agricultural land use on Earth (Ramankutty et al., 2008).

**Gridded livestock of the world**: This layer provides modelled livestock densities of the world, adjusted to match official national estimates for the reference year of 2005, at a spatial resolution of 3 min x 3 min latitude-longitude (Robinson et al., 2014).

**Baseline water stress** (BWS): This is an indicator of relative water demand and is calculated as the ratio of local water withdrawal over available water supply for the baseline year of 2010 (Gassert et al., 2014). Use and supply are estimated at the hydrological catchment scale.

The conceptual approach uses a non-compensatory model to combine the different proxy indicators of drought exposure. Using this methodology, superiority in one indicator cannot be offset by an inferiority in some other indicator. Thus, a region is highly exposed to drought if at least one type of assets is abundant there. For example, an agricultural region that is completely covered by rainfed crops is fully exposed to drought, independently of the presence of other elements at risk. Details of each exposure determinant can be found in Box 2 and maps of their spatial distribution are shown in Figure 5.

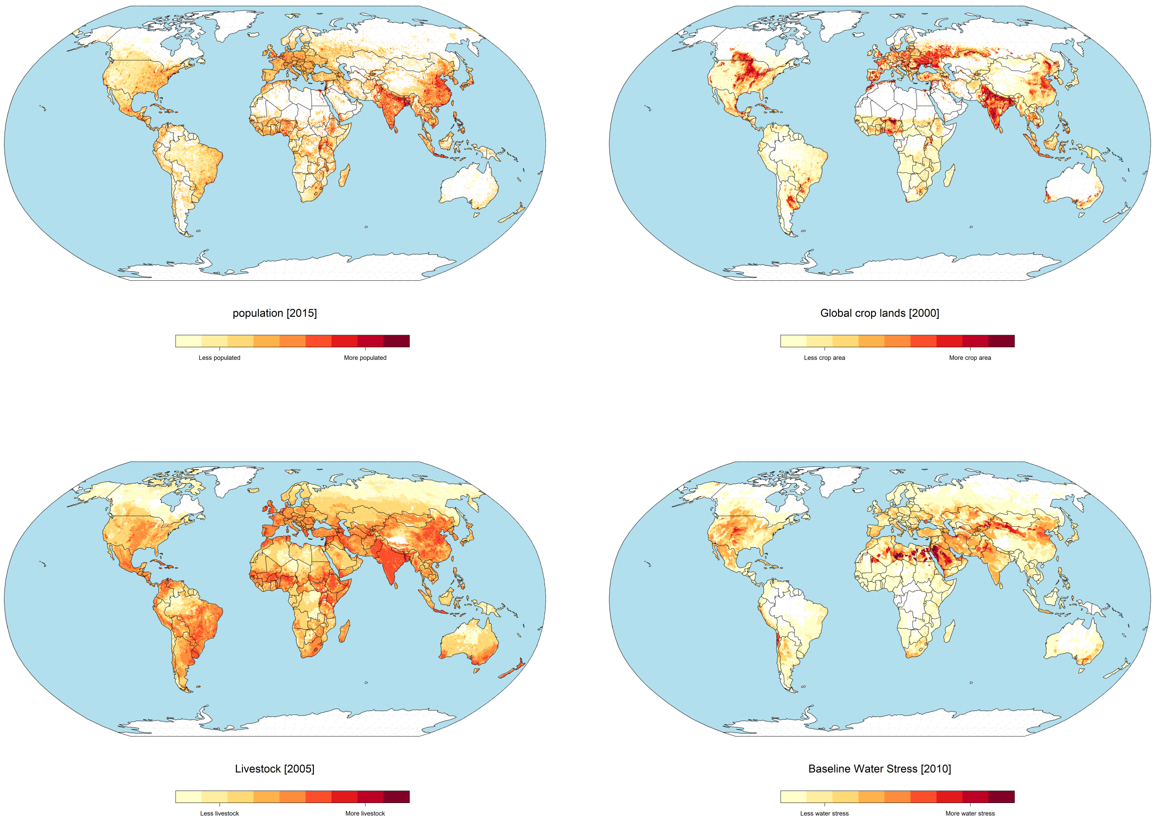



***Figure 5.*** *a) GHS population estimates for 2015. Distribution and density of population, in number of people per grid cell, b) Global agricultural lands, in percent croplands per grid cell, c) Global distribution of livestock in number per grid cell and d) Baseline Water Stress: Total annual water withdrawals (municipal, industrial, and agricultural) as a percent of the total annual available flow.*

### 3.2.3 Assessing the vulnerability

**Vulnerability** assessments are a key component of any drought risk estimation as they support the design of mid- and long-term preparedness actions and water resources planning to targeted sectors or more sensitive populations. Particularly, interventions to reduce drought impacts should be oriented on mitigating the vulnerability of human and natural systems.

In the present framework, vulnerability to drought is represented by a multidimensional model composed by social, economic and infrastructural factors. Social vulnerability is linked to the level of well-being of individuals, communities and society; economic vulnerability is highly dependent upon the economic status of individuals, communities and nations; while infrastructural vulnerability comprises the basic infrastructures needed to support the production of goods and sustainability of livelihoods. This definition of vulnerability is in line with the framework proposed by UNISDR (2004) where vulnerability is defined as a reflection of the state of the individual and collective social, economic and infrastructural factors of a specific region. Such factors may be viewed as the foundation on which local plans for reducing vulnerability and facilitating adaptation are built (Naumann et al., 2014).

According to this theoretical framework, each factor is characterized by generic proxies that reflect the level of quality of different constituents of a civil society and its economy (Naumann et al. 2018b). This follows the concept that individuals and populations require a range of independent factors or capacities to achieve positive resilience to impacts and that no single factor on its own is sufficient to yield all the many and varied livelihood outcomes that societies need to cope with disasters.

As represented in Figure 6 (bottom panel) the most vulnerable regions to drought are located in Central America, Northwest South America, Central and South Asia, and almost the entire African continent, except for some areas in Southern Africa. These results match the outcomes of other authors (e.g. Brooks et al. 2005), which classified nearly all nations situated in sub-Saharan Africa among the most vulnerable to climate disasters.

### 3.2.4 Assessing the drought risk

Figure 6 presents the three components of drought risk and Figure 7 the resulting global drought risk map. As described in Carrão et al. (2016), the three components of risk were aggregated following a multivariate and non-parametric linear programming algorithm (Data Envelopment Analysis). The values for each component are not an absolute measure, but a relative statistic that provides a regional ranking of potential impacts (hotspots) with which on can prioritise actions to reinforce adaptation plans and mitigation activities. Figure 7 shows that on a global scale drought risk is generally higher for highly exposed regions - mainly populated areas and regions extensively exploited for agriculture - such as South and Central Asia, North Eastern China, the Southeast South American plains, Southern, Central and Eastern Europe and the Midwestern United States.

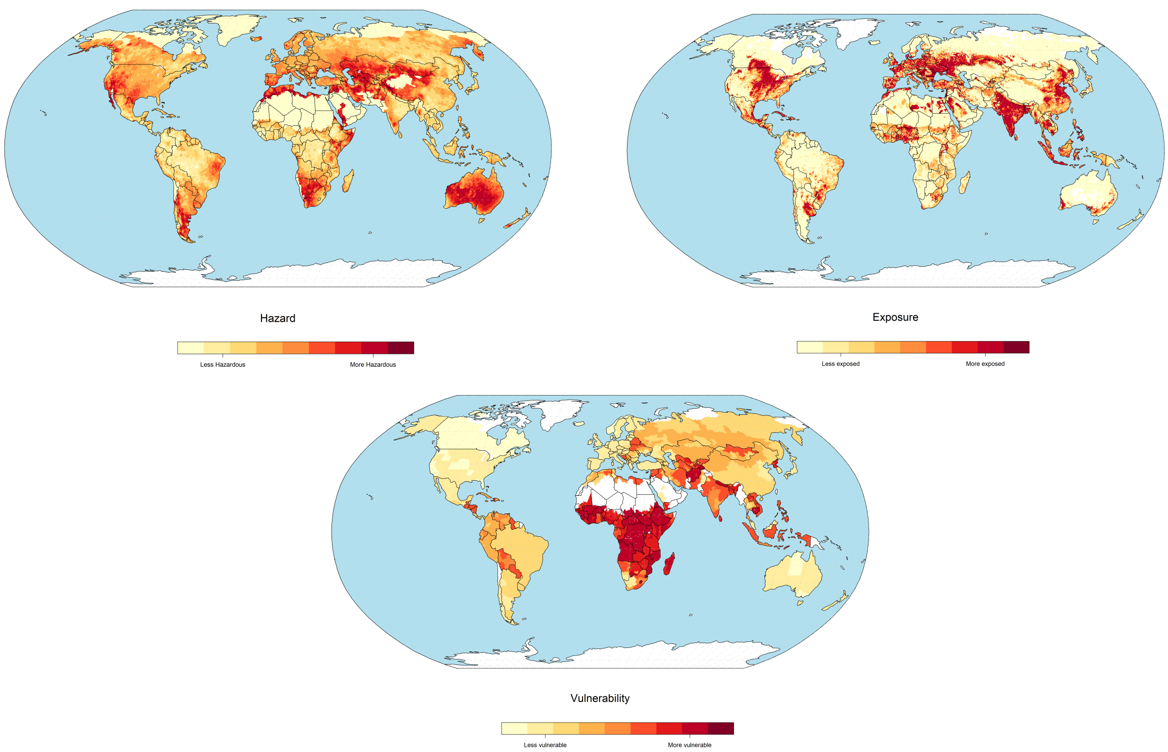



**Figure 6.** Global Drought Hazard according to the Weighted Anomaly of Standardized Precipitation (WASP) Index (upper left), Exposure (upper right), and Vulnerability (lower panel).

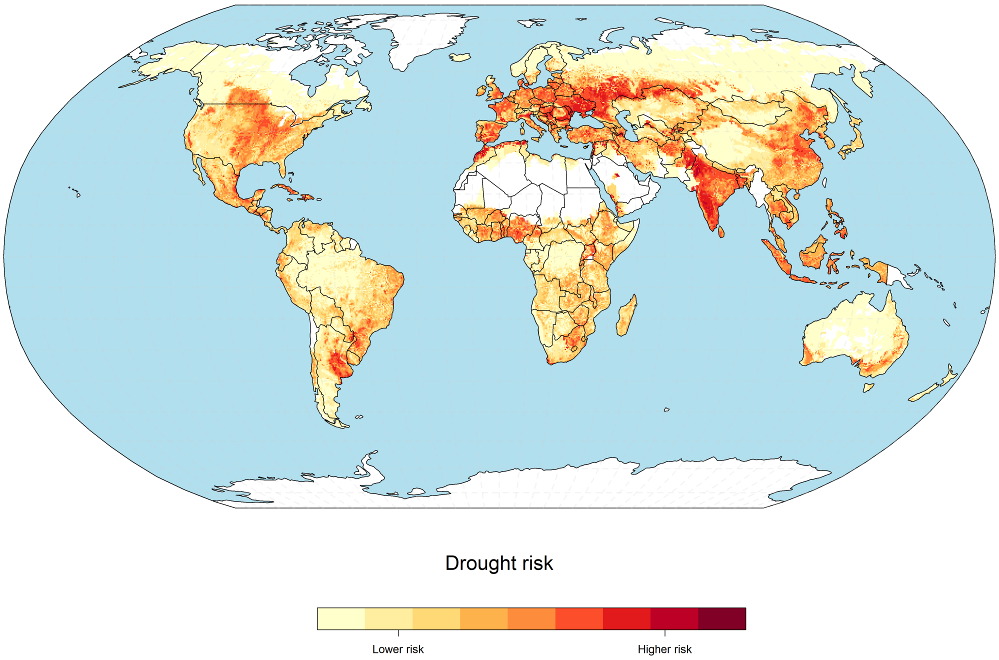



***Figure 7.*** *Drought Risk based on the risk components shown in Figure 6.*

Several factors of uncertainty have to be considered in such analysis, since the metrics involved are partially subjective and conditioned by the data availability at global scale. Indeed, as exemplified above, agricultural drought can be quantified by a number of different indicators, each one able to provide a valid estimate of the different components of drought risk. As an example, Figure 8 depicts the drought hazard map according to the soil moisture-based Yearly Drought Severity Index (YDSI), which quantifies the simultaneous occurrence of a soil water deficit and extremely rare dry conditions (Cammalleri et al., 2016). It could replace or be combined with the WASP index used in the upper left panel of Figure 6.

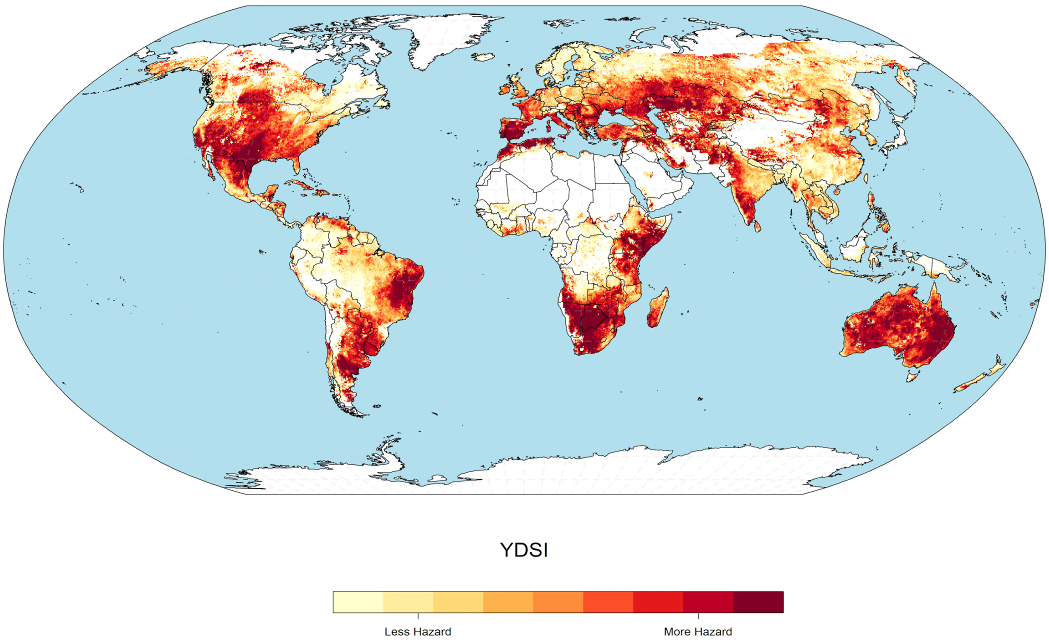



***Figure 8****. Drought Hazard according to the Yearly Drought Severity Index (YDSI).*

Even if it is possible to observe analogies in the general patterns between the drought hazard map in Figure 6 (upper-left panel) and the one in Figure 8, it is evident how different conclusions at local scale can be obtained by using one indicator rather than the other.

## 3.3 Considerations for Other Sectors

The assessment presented above is targeted to the agricultural sector and other primary activities. However, the methodology can be implemented and re-calibrated for analysing the risk in other sectors, such as energy production (hydropower generation, cooling of thermal and nuclear plants), navigation and transportation (waterways), public water supply, or recreation, which should be part of any comprehensive drought risk management plan.

In the case of other sectors and related drought types, such as hydrological drought, the divergence in the spatial patterns of the **hazard** can be even bigger when adopting a more suited indicator. Indeed, indicators related to streamflow and river discharge rather than soil moisture and precipitation better capture the drought hazard for energy production and navigation. An example of such an indicator is the one reported in Figure 9, where the hazard is represented by the number of hydrological drought events observed in a fixed time window (1980-2013) according to the low-flow index described in Cammalleri et al. (2017). This indicator detects un-broken sequences of river discharge below a daily low-flow threshold. It is clear how the number of events is just one of the possible metrics that can be used to quantify the "average" hazard of a hydrological drought in a region.

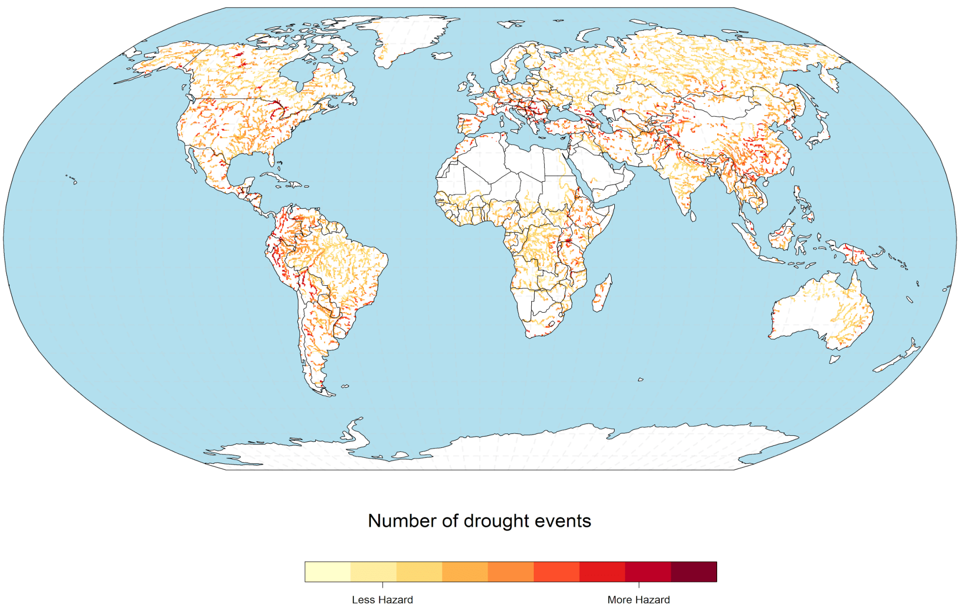



***Figure 9.*** *Drought Hazard according to the number of events detected by the low-flow index.*

Also in this case, even if some analogies in the patterns can be noticed between Figure 9 and Figures 6 and 8, one can see different hot spots not observable in the latter. Several analogous maps of drought hazard and severity can be found in the scientific literature, including the ones based on SPEI by Spinoni et al. (2014), or the one reported in Sheffield and Wood (2007) available in the AQUEDUCT water risk atlas[1].

[1]http://www.wri.org/applications/maps/aqueduct-atlas

The foregoing brief discussion exemplifies how the maps reported in Figures 6, 8 and 9 are just a few of the possible depictions of drought hazard, which quantification is strongly dictated by the final goal of the risk study, as well as by the socio-economic sector of interest. This highlights the complexity in providing a definitive measure of drought hazard. Similar arguments can be made for drought vulnerability and exposure, which characterization is even more fundamentally related to the factors considered relevant for the analysis. Factors relevant for assessing agricultural exposure and vulnerability may be irrelevant for energy production and vice versa, for example.

Even within a specific economic sector, the options for representation and quantification of risk and its components are multi-faceted. As an example, the case for **power generation** is analysed. Power plants may depend on water directly (hydropower) and indirectly (cooling systems of generators). In both cases, insufficient water implies a reduction or a halt in energy production. Power plants typically use superficial waters (DOE, 2014), therefore they are affected by hydrological droughts and consequent low stream flows.

In terms of hazard, this translates into the likelihood of missing or reduced water intake at the installation. It must be noted that high water temperatures in input or output and legally binding minima/maxima are more often an issue for plant operations. However, these do not necessarily entail low flows, and vice versa, and may be treated as a separate issue from drought. An indicator such as the low-flow index of Figure 9 may provide a good indicator for the drought hazard for energy production. While the use of meteorological drought indices, such as SPI, has been tested for limited geographical domains (e.g. Barker, 2016; Bayissa et al., 2018), a general correlation with hydrological droughts could not be established at global scale.

Concerning **exposure**, since electricity can be transported over long distances from the source and across national boundaries, identifying people and assets potentially affected by reductions in power output is a difficult task. However, installed power capacity itself is a proxy for exposure (Figure 10): the higher the capacity, the higher the exposure, as presumably more electricity demand is relying on it.

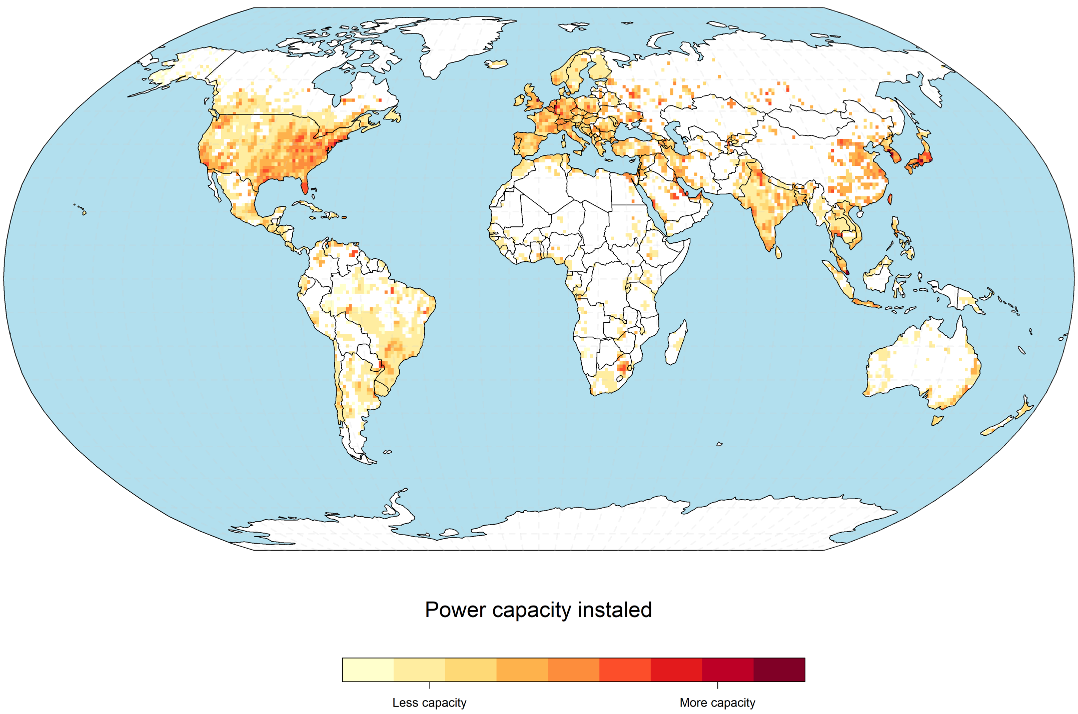



***Figure 10.*** *Map of installed power capacity (GW), whose facilities depend on water directly (hydropower) or indirectly (generators cooling) (Data sources: IAEA-PRIS (nuclear), GrAND database (hydro), Global Energy Observatory (other thermal)).*

Indeed, this idea was applied in the impact analysis by van Vliet et al. (2016), and is based on the assumption that, even if power plants are not operated at full power all the time, when energy demand is high their full capacity is critical, especially when this occurs during warmer and drier periods. An advantage of using power capacity is that thorough data is available for individual installations at global level (e.g. GEO et al., 2018; UDI, 2015).

On the other hand, actual energy demand in a given time interval may provide a less conservative but more accurate estimate of exposure. Such specific information is available only for a limited number of power plants worldwide, while the only consistent data are found at national scale, such as yearly electricity consumption per capita. These data can be downscaled through population data (Figure 11), but with some caveats. First, the per capita consumption refers to the whole consumption, regardless of the use. Industrial sites in sparsely populated areas, for example, will strongly influence the per-capita consumption in the related mapping unit. Second, it assumes that electricity consumption and generation are located closely, therefore a drought occurring at an important but remote power plant will not show up. Third, demand is equated to consumption, i.e. all demand is met.

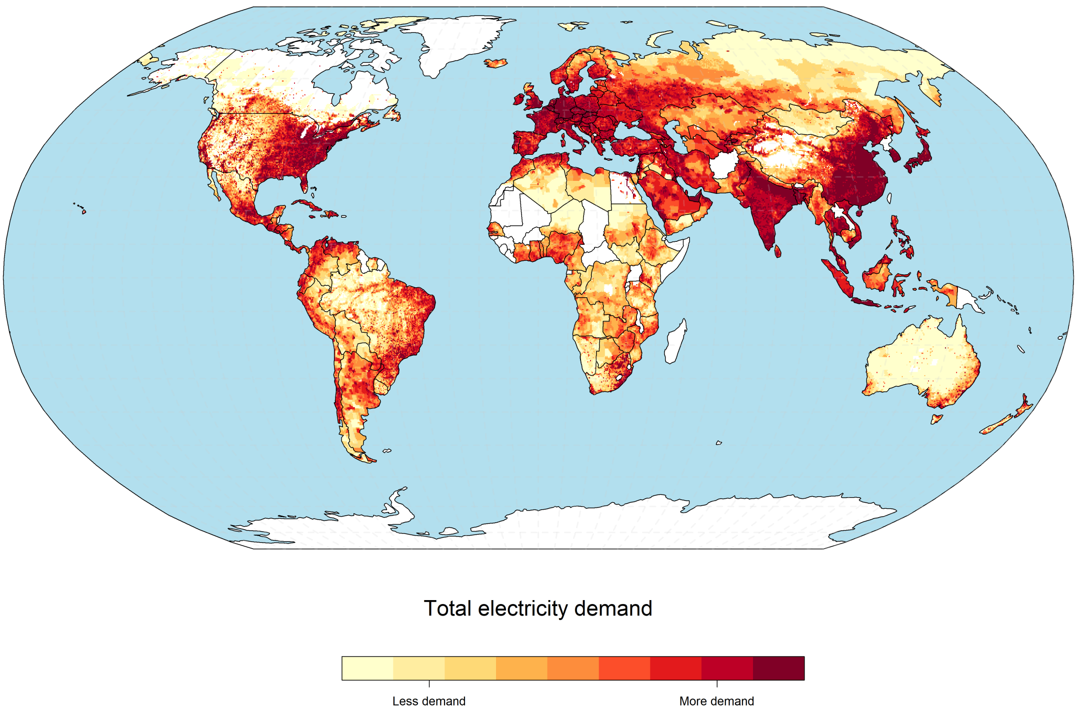



***Figure 11.*** *Map of total electricity demand by population, as the yearly national electricity consumption per capita (KWh) times population in 2015. Note that all non-domestic uses are included as well (Data sources: World Bank and CIESIN).*

Finally, **vulnerability** to droughts refers to the means available to mitigate the lack of water. Conceptually, this may have several definitions depending on the context and the scale of analysis. At power plant level, essentially it relates to the amount of water required to produce a unit of energy. This depends on many technological features, but primarily on the cooling technology (for thermoelectric power plants, see Macnick et al., 2012) or the head (for hydropower the height difference between the input and output water), plus the volume of water storage available relative to the size of the installation.

From a broader perspective, country statistics about the energy sector can provide a wide range of indicators that are helpful to understand and model overall vulnerability to droughts. Examples are the ratio between energy sources dependent and non-dependent from freshwater (Figure 12), the diversification of fuel types (which usually entails different capacity factors), the percentage of electricity imports on total use, the amount of freshwater resources per capita, the ratio of water use for energy production against the total, the electricity prices evolution, etc. Each of these descriptors may be combined to show specific aspects of vulnerability at country scale. Table 3 provides a summary of possible risk components at different spatial levels.

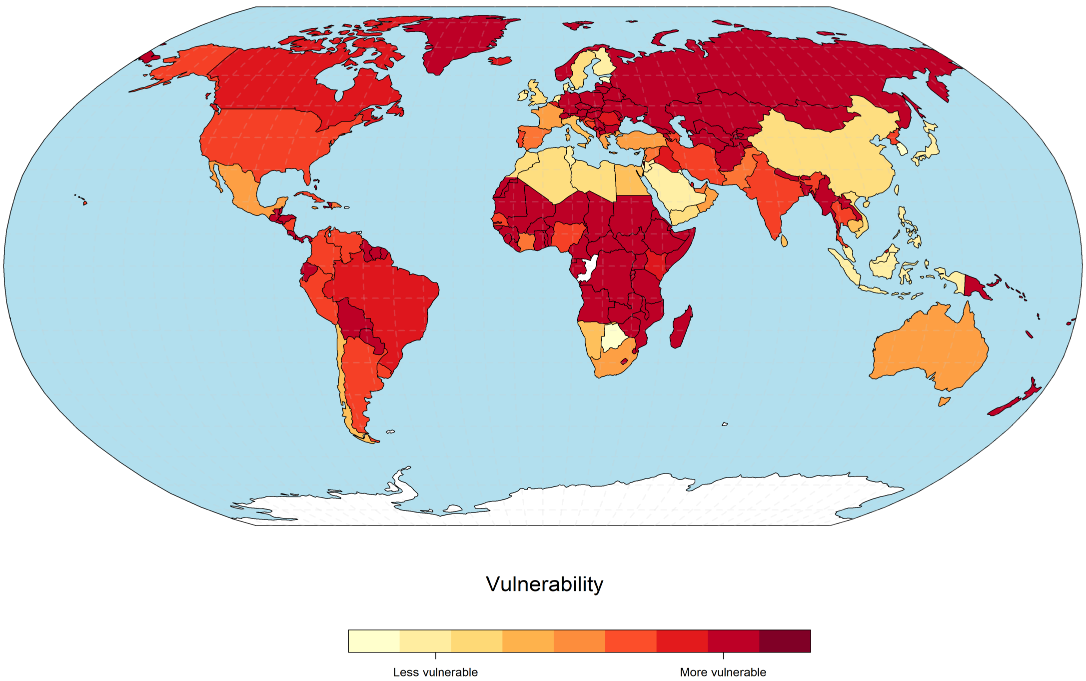



***Figure 12.*** *An example of a vulnerability map based on the ratio between power sources dependent and non-dependent from fresh waters. Power generators that do not need water for cooling or use seawaters have no vulnerability to droughts.*

Ideally, with specific information on power plant features, it would be possible to represent and upscale vulnerability from individual power plants to global scale. However, data on the power sector is still dispersed, uneven and sometimes inaccessible, but harmonized data sources are constantly evolving and improving (e.g. GEO et al., 2018; UDI, 2015). As an example of a dynamic risk assessment at power plant level, Figure 13 shows the situation in Europe during the abnormally hot and dry summer of 2003, when several power plants had to reduce their output because they could not divert enough cooling water either physically or legally from the rivers (Fink et al., 2004). The map highlights the rivers most affected by low flows across Europe during the end of August, by means of the low-flow index (Cammalleri et al., 2017), and the nuclear power plants downstream at risk of power reductions. Indeed, several of those depicted had to reduce operations due to low water intakes and/or high water temperature (e.g. Saint-Alban, Bugey, Tricastin, Nogent-sur-Seine, Cruas, Isar).

***Table 3.*** *Possible indicators for risk components for power generation at three spatial and conceptual levels.*

| Scale | Exposure | Vulnerability | Hazard |
|---|---|---|---|
| **At power plant** | Plant capacity (MW);<br>Energy production (MWh) | Water withdrawal ($m^3$/MWh) and water storage capacity relative to power capacity | Low flow at power plant intake |
| **Basin** | Sum of power plants capacity (MW);<br>Sum of energy production (MWh); | Average/maximum vulnerability of plants by basin. | Low flow at basin outlet;<br>Long-term meteorological drought (SPI) |
| **Country** | Sum of power plant capacity (MW);<br>sum of energy production (MWh);<br>Energy consumption (MWh) | Ratio of water dependent and non-dependent power sources;<br>Diversification of sources;<br>Percent energy import;<br>capacity factor | Historical frequency of drought occurrence;<br>Weighted average of long-term meteorological drought (SPI) by basins |

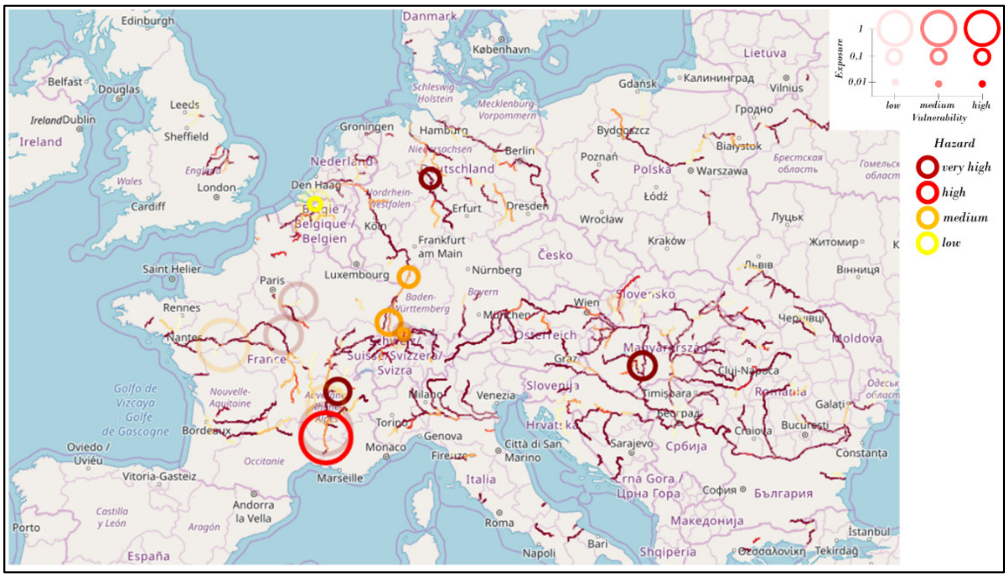



***Figure 13.*** *At the end of August 2003, due to the ongoing drought, several power plants in Europe were exposed to low flow conditions. The three dimensions of risk for power generation are represented as follows: As a proxy for exposure, the circle size is proportional the gross power capacity of the station (circles from smaller to bigger correspond from about 500 to 4000 MW); the hazard is represented by the low flow anomalies over the rivers affected (yellow, orange and red streams) and the river intake (circle colour); the transparency level of circles highlights the level of vulnerability associated with the cooling system, with the more intense colours related to the more vulnerable (i.e. a higher amount of water required per unity of energy output).*

## 3.4 Scale considerations

Besides the highlighted differences in hazard, exposure and vulnerability between sectors, the risk assessment is also dependent on the scale of analysis. This is due to the generally increasing detail of input data when moving to smaller spatial domains. As such the presented methodology allows rescaling the analysis over different spatial domains and therefore to obtain useful results at different scales of analysis. These can range from the farm level to the continent and the global level, thus allowing analysing the spatial distribution of the drought risk within a given area of interest (e.g. farm, country, region, continent, global).

As this framework is data driven, more socio-economic data at local level are required to obtain reliable estimates. Indeed, wherever this information is available it allows tailoring the analysis and to set adaptation strategies fitted to local requirements and specific sectors that might be adversely affected by droughts.

Figure 14 shows the same analysis as shown in Figure 6 and 7 for the global level, based on the same global data re-scaled for the domain of Argentina. The country analysis shows that vulnerability in Argentina is higher in the northern part of the country due to lacking infrastructures and slow social progress. The differences between the global and national assessments are mainly related to local changes in vulnerability produced by regional inequities. González (2009) stressed a similar pattern of social vulnerability, which is characterized by the historical backwardness in the Northeast and Northwest regions.

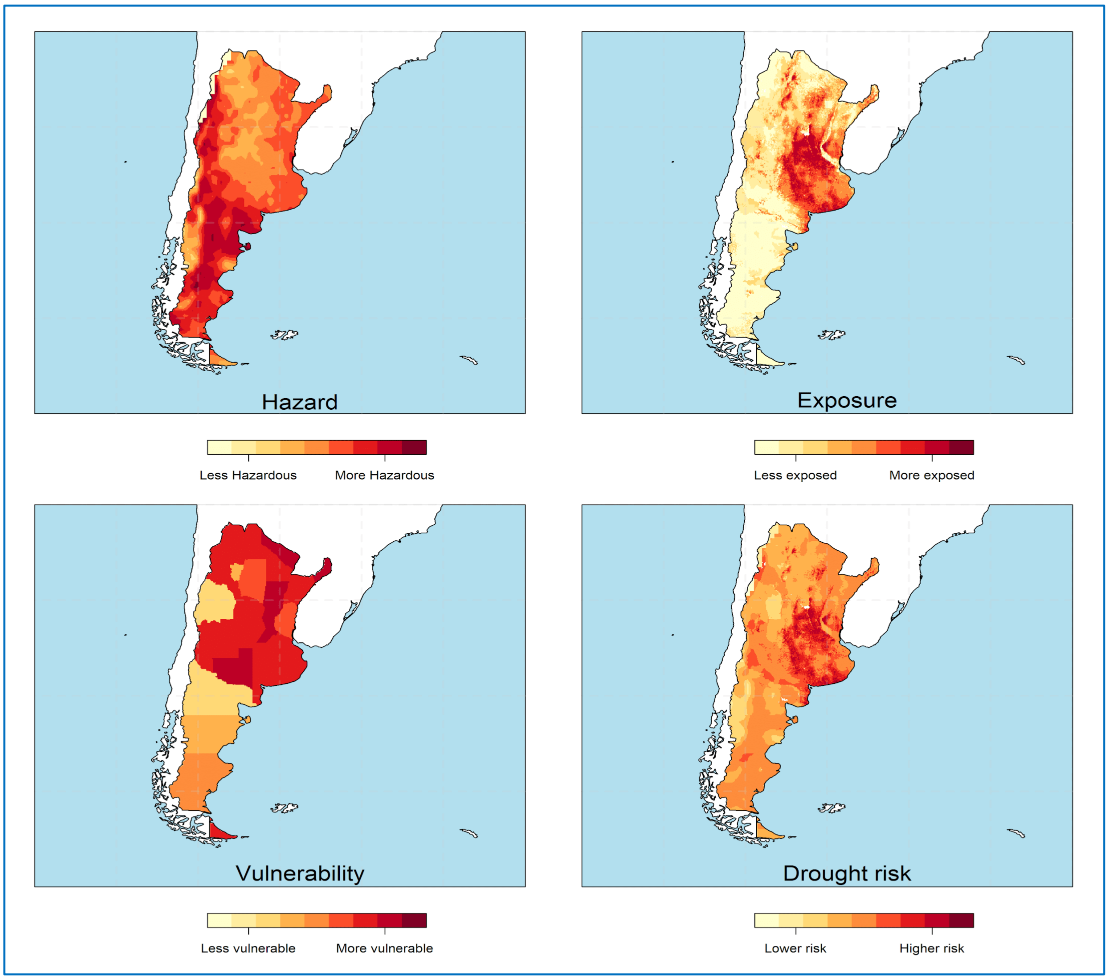



***Figure 14.*** *Drought Hazard, Exposure, Vulnerability and overall drought risk for Argentina.*

Combining the vulnerability with the hazard and the exposure, however, shows that the drought risk is lower for remote regions, and higher for populated areas and regions extensively exploited for crop production and livestock farming, such as the Buenos Aires, Córdoba and Santa Fe provinces located in the centre of the country. On the other hand, the regions characterized by a lower or almost null exposure are characterized with a lower drought risk. Since the remaining regions are still subject to severe drought events as well, their risk increases as a function of the total exposed entities (mainly croplands) and their local coping capacity.

The global map of drought risk (Figure 7) shows the same general pattern, albeit with less gradual differences within the country, which is due to the relative re-scaling of the input variables. Injecting more detailed national data would most likely result in more spatial differentiations. However, the large-scale pattern would not change as long as the global datasets correctly represent the general differences within the country.

# 4 Drought Impacts

## 4.1 Introduction

Drought impacts affect almost all parts of the environment and society. Unlike other natural hazards such as floods, earthquakes or hurricanes that result in immediately visible, mostly structural damage, droughts develop slowly. Frequently, drought conditions remain unnoticed until water shortages become severe and adverse impacts on environment and society become evident. Drought impacts may be influenced by adaptive buffers (e.g. water storage, purchase of livestock feed) or can continue long after precipitation has returned to ‘normal’ (e.g. owing to groundwater or reservoir deficits). The slowly developing nature and long duration of drought, together with a large variety of impacts beyond commonly noticed agricultural losses, typically makes the task of quantifying drought impacts difficult (Wilhite, 2005).

Impacts of droughts can be classified as **direct** or **indirect** (Tallaksen and Van Lanen, 2004; Meyer et al., 2013, Spinoni et al., 2016). Table 4 presents different sectors that might be adversely affected by droughts. Examples of direct impacts are limited public water supplies, crop loss, damage to buildings due to terrain subsidence, and reduced energy production. Because of the dependence of livelihoods and economic sectors on water, most of the drought impacts are indirect. These indirect effects can propagate (cascade) quickly through the economic system affecting regions far from where the drought originates. Indirect impacts relate to secondary consequences on natural and economic resources. They may affect ecosystems and biodiversity, human health, commercial shipping and forestry. In extreme cases drought may result in temporary or permanent unemployment or even business interruption, and lead to malnutrition and disease in more vulnerable countries. Drought-related damages may further be classified as **tangible** (market related) or **intangible** (non-market related). The latter are particularly difficult to quantify, including, for example, ecosystem degradation or the costs long-term adaptation measures.

The physical effects of drought on human societies are well documented for many case studies and some global analyses (Carrão et al., 2016; Bachmair et al., 2017; Naumann et al., 2015; Rowland et al., 2015). Nevertheless, due to the complex interactions between different economic sectors, cascading effects and indirect impacts, it is difficult to quantify the overall impacts of droughts. Certain demographic or socioeconomic factors worsen the intrinsic vulnerability to drought-related impacts.

Reports of drought impacts are available from the media, governmental or other official reports, and/or scientific papers. However, the fact that only part of the drought damages are of direct and tangible nature, combined with the often prolonged duration of droughts and the delayed and/or spatial dislocated occurrence of cascading effects make it extremely difficult to retrieve spatially and monetarily correct loss estimates. In the few disaster databases that are publicly available, drought disasters, therefore, are particularly underreported (Svoboda et al., 2002). According to Gall et al. (2009), for example, droughts account for less than 7% of total losses from natural hazards since 1960. Following the above considerations, such values should be interpreted with care since until today there is a significant gap between the reported and real drought impacts that hinders their systematic quantification.

Figure 15 shows the expected annual damage due to droughts according different impact databases. Developed and bigger economies like the United States, Australia, China or Brazil, suffer most from economic consequences of droughts. Less developed countries, however, do face more direct or indirect impacts on the population.

***Table 4.*** *Description of the main sectors affected by droughts.*

| Sector | Description |
|---|---|
| **Economic impacts** | A water deficit induced by droughts affects production, sales and business in a variety of sectors. |
| **Socio-economic impacts** | Welfare changes experienced by human beings should be accounted for in the measures of the socioeconomic impacts of drought. The social impacts of drought can affect people's health and safety, cause conflicts between people when water restrictions are required, and may result in changes in lifestyle. |
| **Impacts on environment, forestry, wildfires, and biodiversity** | Drought affects the environment in many different ways. Plants and animals depend on water, and under drought conditions their food supply can shrink and their habitat can be damaged. Sometimes the damage is only temporary and their habitat and food supply return to normal when the drought is over. But sometimes drought impacts on the environment can last a long time, or may lead to permanent land and ecosystem degradation. |
| **Impacts on farming and livestock** | Farmers might be adversely affected if a drought damages their crops. They may spend more money due to increasing irrigation costs, drilling new wells or feeding and providing water to their animals. Industries linked with farming activities, such as companies that make tractors and food, may lose business when drought damages crops or livestock. |
| **Impacts on public water supply** | Drought conditions impact water supplies by decreasing supply and increasing demand for various usages (industrial, agriculture or residential use). |
| **Impacts on surface and groundwater** | Direct impacts of droughts on surface waters include reduced river flows and reservoir levels. Significant decreases in aquifer levels are the main expression of drought impacts on groundwater. |
| **Impacts on power generation: hydropower, thermal, and nuclear** | Hydroelectricity production is related to the amount of water stored in the upper reservoirs, the production level can be lower during a drought. Peak demands for electricity then need to be satisfied by other means available in the short term (e.g. gas turbines). The amount of losses depends on hydroelectricity infrastructures and drought severity. Reduced availability of cooling water can force the reduction of power generation and even shutdown of thermal or nuclear power plants during droughts. |
| **Impacts on commercial shipping** | During low-flow conditions, barges and ships may have difficulty in navigating streams, rivers, and canals because of low water levels, affecting businesses that depend on water transportation for receiving or delivering goods and materials. People might have to pay more for food or fuel as a result. |
| **Impacts on tourism and recreation** | Since many activities in the tourism sector are water-related, droughts can bring critical losses. Droughts have impacts on both summer and winter activities. |

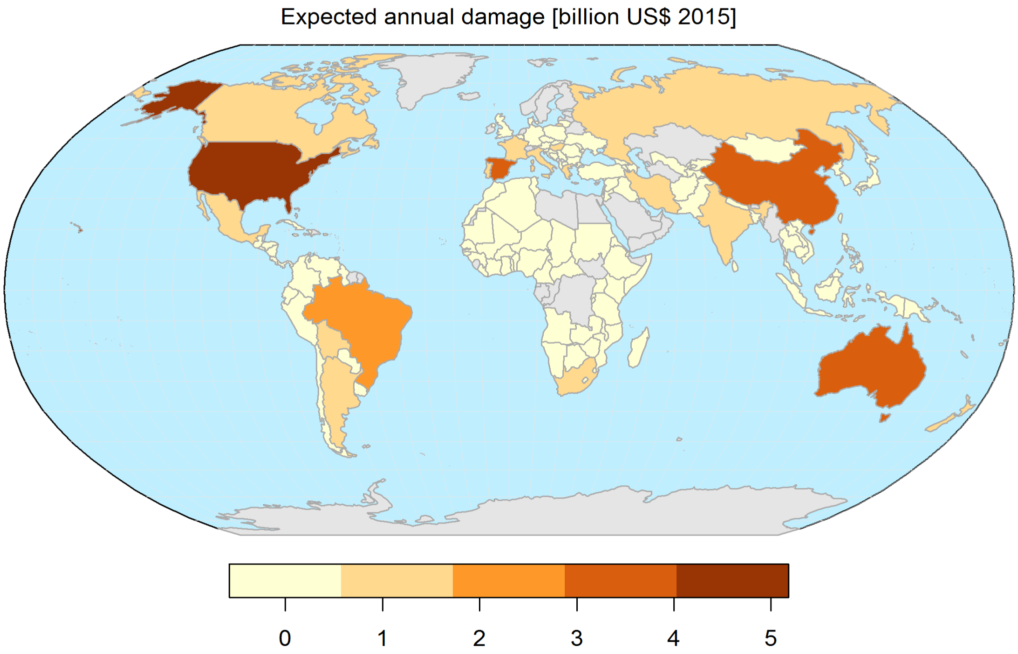



***Figure 15.*** *Expected annual damage due to droughts in billion US$ (Data sources: NatCatSERVICE, EM-DAT and DesInventar).*

Indeed, economic damage from single drought events can be catastrophic, with a single drought event capable of causing billions of US$ of damage. In term of losses, the most severe events can lead to significant losses and can affect the economy of an entire region or country. For instance, according to NatCatService[2] data, the severe drought in California during 2006 caused losses of up to 4.4 billion US$ and during the 2013-2015 drought in the Midwest of the United States the reported losses amounted up to 3.6 billion US$. The 2013-2015 drought that affected central eastern Brazil (mainly, São Paulo, Minas Gerais and Rio de Janeiro) was linked to reported losses of about 5 billion US$. The 2010-2011 drought in the Horn of Africa is estimated to have caused up to a quarter of a million deaths, and to have left over 13 million people in the region dependent on humanitarian aid. At the same time US$1.3 billion were spent on drought-relief measures (UNOCHA, 2011).

Among all economic activities, agriculture is one of the sectors most affected by droughts in developing countries. To identify trends in the economic impact of disasters on crops, livestock, fisheries and forestry, FAO (2015) recently reviewed 78 post-disaster needs assessments undertaken in the aftermath of medium- to large-scale disasters in 48 developing countries in Africa, Asia and Latin America over the past decade (2003–2013). According to this report, agriculture absorbs on average about 84 percent of all the economic impact in these countries. Livestock is the second most affected subsector after crops, accounting for US$ 11 billion, or 36 percent of all damage and losses reported in the post-disaster needs assessments, where almost 86 percent of these damage and losses were caused by drought events.

Environmental conditions affect plants and their productivity during all phases of growth and development. These conditions include water availability, solar radiation, temperature, but also soil properties like acidity, etc. Studies show that changes in biomass production of a barley crop decreased in response to droughts of various timing and duration (Jamieson et al. 1995). More directly, moisture stress in all growth stages reduced the grain yield significantly, (Singh et al. 1991). Hlavinkaa et al. (2009) found that severe droughts are linked with significant reduction in yields of the main cereals and the majority

[2] https://natcatservice.munichre.com/

of other crops throughout the most drought prone regions. For example, they found a statistically significant correlation between drought indicators summed during the main growing period of each crop and their yield.

Climate change is likely to increase the frequency and severity of meteorological and agricultural droughts in presently dry regions by the end of the 21st century. Particularly vulnerable are countries located in arid and semi-arid regions where water stress will be further exacerbated due to an increasing strain from overexploitation and land degradation already tangible under the present conditions (IPCC 2014). As a consequence, many other economic sectors and ecosystems are likely to be adversely affected by climate change. For instance, freshwater-dependent biota will suffer not only directly from changes in flow conditions but also from drought-induced river temperature increases linked to discharge reductions (Van Vliet et al., 2011). Decreases in soil moisture and increased risk of agricultural drought are likely in present drylands and the agricultural risk in these areas is projected to increase with medium confidence by the end of this century (IPCC 2014). This might lead to an increased risk of food insecurity and breakdown of food security, particularly relevant for poorer populations in urban and rural settings. In many countries, increased fire risk, longer fire season, and more frequent large, severe fires are expected as a result of increasing heat waves in combination with drought (Duguy et al., 2013).

The health of human populations is sensitive to shifts in weather patterns and other aspects of climate change. These effects occur directly, due to changes in temperature and precipitation and in the occurrence of heat waves and droughts. Human health may be affected indirectly by climate change-related ecological disruptions, such as crop failures or shifting patterns of disease vectors, or by social responses to climate change, such as displacement of populations following prolonged drought, and the elderly face disproportional physical harm and death from heat stress and drought (IPCC 2014, van Lanen et al., 2017).

## 4.2 Case Studies

### 4.2.1 Argentina (Impact on market oriented agriculture)

Agriculture is a pillar in the economy of Argentina, at about 8% of the total GDP. In the central and north-eastern regions of the country, plains or lowlands are predominant and host highly productive soils devoted to large-scale agriculture. In particular, Argentina is the world's number three exporter of soybean and maize, which together made up 38% of all exports from the country in 2016. Regarding the production of cattle, during the same period, the country was the 6th producer with a stock of 52 million heads and the 4th producer of meat (2.6 million tons). As a consequence, the economy is especially vulnerable to the effects of extreme weather on agricultural production. The annual precipitation is abundant across the area and fluctuates little from year to year, so planting of the main crops is generally done to take advantage of summer rains in December and January, with harvests between January and April (for maize) and between March and May (for soybean). Most of the agricultural production in Argentina relies on rainfed extensive farming with only 5% of cultivated land under irrigation.

In late 2017, a severe drought hit northeastern Argentina, including most of the land used for intensive agriculture, causing major damages to primary production, particularly to soybean and maize crops. The provinces of Buenos Aires, Córdoba, Santa Fe, Entre Ríos and La Pampa were all affected, with a total area close to a million $km^2$ exposed. The drought was sudden and very intense, spanning a few months only, and concurrent with the growth stage of the cropping cycle. The event was monitored by JRC's Global Drought Observatory (GDO)[3], a system that updates the Risk of Drought Impacts for Agriculture (RDrI-Agri) in real time. The RDrI-Agri indicator is based on the combination of vulnerability and exposure factors as described in previous sections and the real time

[3] http://edo.jrc.ec.europa.eu/gdo

evolution of the drought hazard as derived from meteorological, soil moisture and vegetation greenness data.

The drought indicators captured well the drought event at its different stages during the growing season of crops (Figure 16). During the beginning of 2017, precipitation anomalies (SPI) dropped steeply to the "extreme drought" level in a time span of two months only and with a peak in March, while the effects on soil moisture and vegetation greenness were evident from this month onwards and persisted during the following months. The risk indicator (RDrI-Agri, Figure 16d) shows the temporal evolution of the risk of agricultural impacts. The indicator peaked with a large proportion of the area under medium and high risk during the months of March to May.

As a result, about 6.1 million tons of soybean were lost, equivalent to about 30% of the expected yield for the season. Concerning maize, this figure is about 25%. The economic losses were estimated in at least 6 billion US dollars, roughly 0.8 percent of the national GDP growth, with impacts comparable to the big drought event of 2009. Given its weight on the global supply, heavy yield losses in Argentina can cause grain commodity prices to raise in international markets.

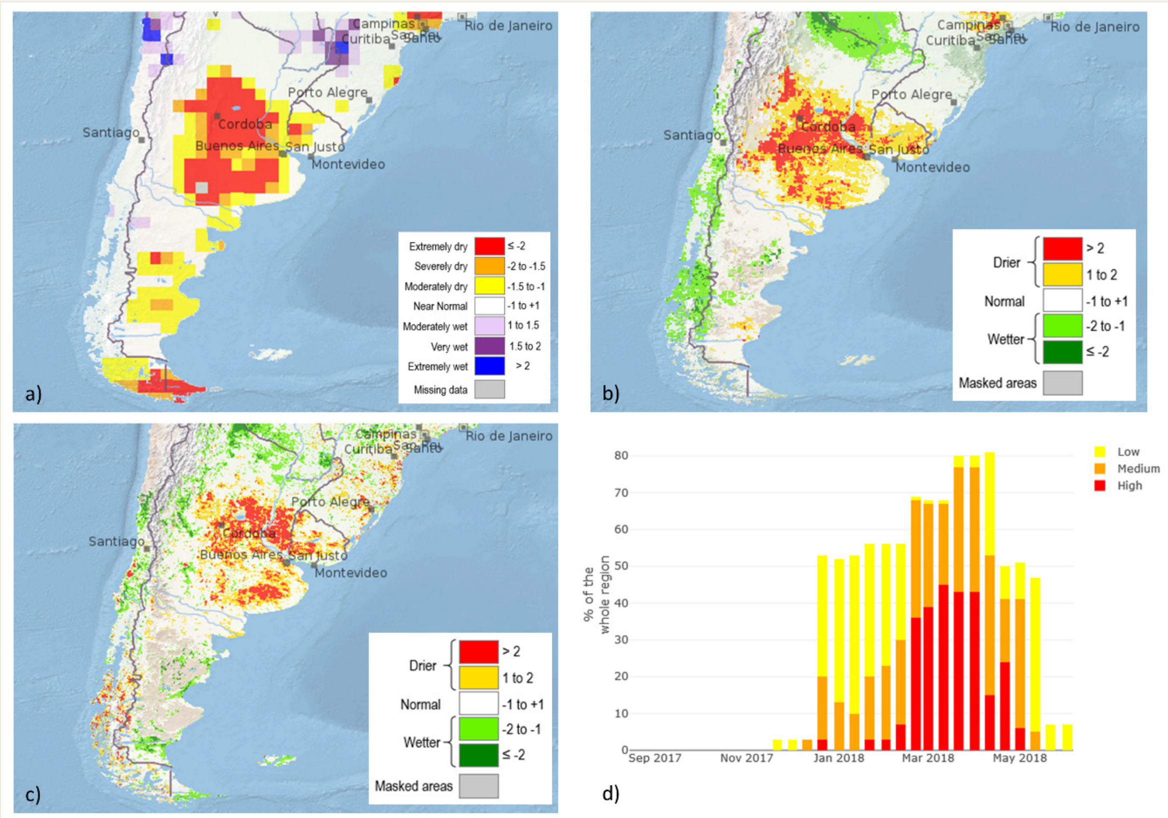



***Figure 16.*** *a) SPI-3: Precipitation anomaly for the three-month accumulation period from January to March 2018, b) Soil moisture anomaly for March 2018 and c) Anomaly in the photosynthetic activity of the vegetation cover (vegetation vigour) for the period 01-04-2018 to 10-04-2018 and d) Time series of the Risk of Agricultural Impacts (RDrI-Agri) indicator for the province of Buenos Aires in percent of the total area. Adjacent regions affected show similar patterns, sometimes reaching 100% (Source: GDO).*

## 4.2.2 South Africa (Impact on public water supply)

Since 2015, the South African province of Western Cape experienced a sustained chain of very low and below-average precipitation periods, resulting in a hydrological drought that further intensified in the season between April and September 2017, being much drier than usual. The precipitation deficit slowly piled-up to become, in early 2018, the worst drought recorded in the region in a century, and a true emergency for the city of Cape Town. This is one of the biggest urban areas of the country, but most municipalities in Western Cape region saw an increase of the alert level as well, totalling a population exposed of over four millions.

During this multi-annual drought, the water deficit propagated through the hydrological cycle, and the water reservoirs that supply the city of Cape Town with drinking water were heavily affected.

Short-term meteorological indicators (e.g. SPI-3) do not detect any particularly hard conditions at the peak of the drought, as precipitations in the previous quarter were fairly close to normal, suggesting a mild drought at the most. However, longer rainfall accumulation periods (e.g. SPI-24, Figure 17) show the serious lack of precipitation during the previous two years, with SPI values dropping to the exceptional threshold of minus three, marking the "extreme drought" level. This entails a constant under-supply of water to reservoirs since at least early 2015, thus explaining the crisis of water provisioning in the region.

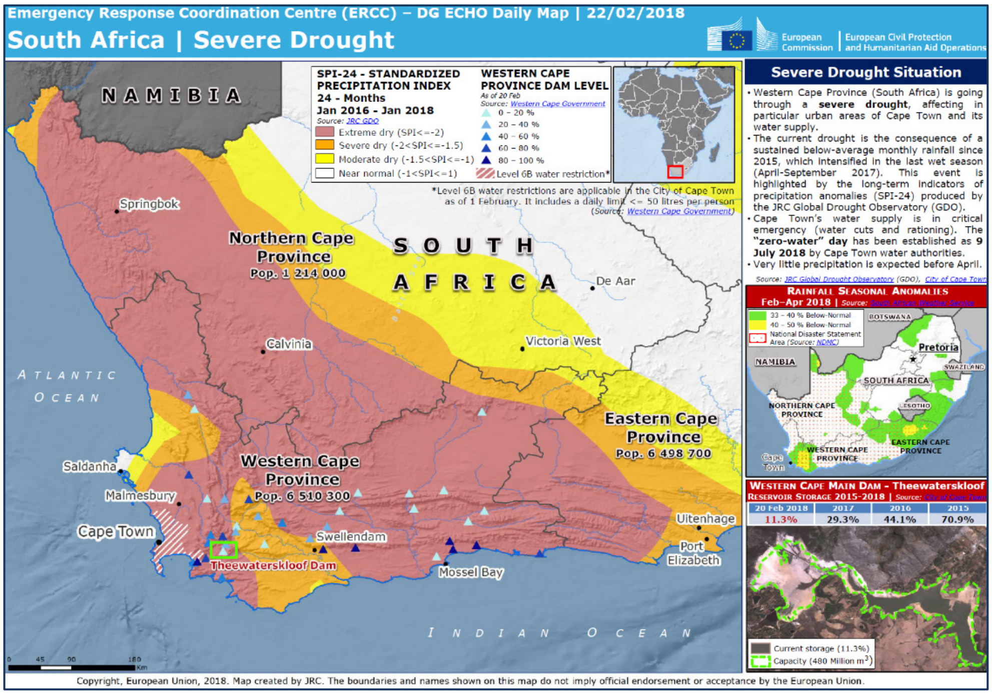



*__Figure 17.__ Map of the severe drought conditions in Western Cape Province, January-February 2018 (Source: DG ECHO Emergency Response Coordination Centre and DG JRC).*

The 12-month SPI series shown in Figure 18 demonstrate the severe precipitation deficits of the winters 2015-2016 and 2017-2018, which are at the basis of the experienced severe hydrological drought conditions.

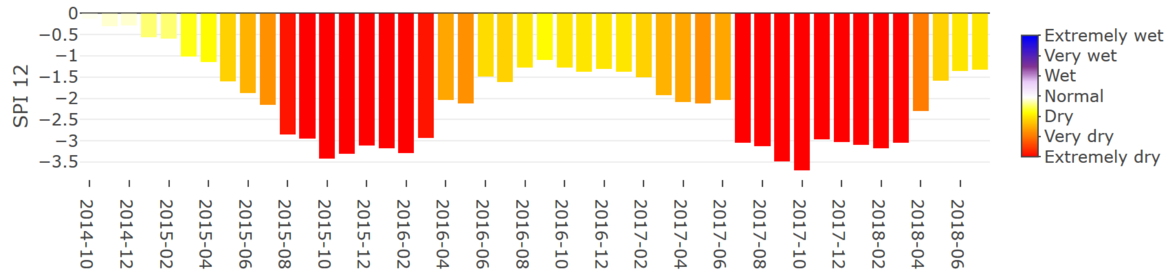



***Figure18.*** Time-series of SPI with a cumulative period of 12 months (SPI-12) reaching extremely low values for many months, indicating a prolonged and severe hydrological drought.

During this event, Cape Town authorities restricted tap water allowance for any use to a mere 50 litres per person per day, a threshold above which the chance of complete closure of the public water supply at the so-called "day zero", would materialize within weeks and population would have been supplied at a limited number of distribution points only.

Due to the relatively dry climate of the region, a number of reservoirs are dedicated to water storage in Western Cape in order to cope with the periodical lack of precipitation, but the situation faced was extraordinary and critically low water levels were recorded, putting in serious distress the water supply chain. The Theewaterskloof Dam, the largest in the Western Cape water supply system, holding 41% of the water storage capacity available to Cape Town, for example, went to critically low levels in early 2018 (about 11% of 480 million cubic metres total capacity, Figure 17, lower right panel). In addition, due to the fast demographic growth of the city in recent years, the water infrastructure hardly kept pace with the demand. Thanks to water rationing and collective water-saving efforts fostered by the government (Figure 19), as well as some precipitation events, the so-called "day zero" was avoided for 2018. However, the complete recovery from this water crisis depends on the replenishment of reservoirs and the operational availability of alternative sources. Indeed, big investments are now being made for desalinization plants.

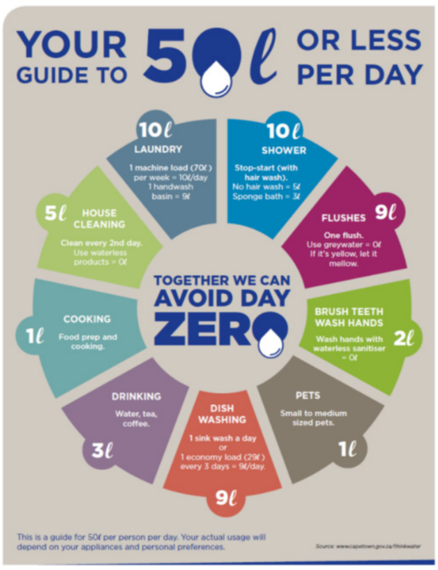



***Figure 19.*** *Guide to deal with a restricted water consumption of 50 l or less per day in Cape Town (Source: www.capetown.gov.za/thinkwater).*

### 4.2.3 Syria (Impact on agriculture, land degradation and conflict)

The conflict in Syria (since 2011), requires a better understanding of the link between the ongoing environmental stresses caused by land degradation and climate change (climate bio-physical stress) and the social stresses (socio-economic status) in that region and how their impacts were likely incubators for Syrian rural areas to explode. Recently, media and analysts suggested that climate change plays an indirect role in the Arab Spring and the Syrian uprising (Friedman, 2013) that was mentioned earlier by Erian et al. (2010) and Erian (2011), when they described the drought impact as one cause of the instability in Syria.

Syria today is not only facing drought but also a severe crisis that reduces its capability to develop resilience against drought risks. In fact, any post-conflict solution is not going to be permanently stable unless measures for developing drought coping capacities and resilience are considered in Syrian rural areas.

Syria is part of the historical region known as "Fertile Crescent Area". This area suffered from recurrent and prolonged droughts. Around 2200 BC, a temporary climate shift created 300 years of reduced rainfall and colder temperatures, which forced people to abandon their rainfed fields in what is now known as northeast Syria, and migrated to the south or turned to pastoralism to survive (Weiss and Bradley 2001).

Nowadays rainfall in Syria represents about 68.5% of the available water sources. Recent studies analysing different indices related to drought, like soil moisture, show increases in the proportion of the overall areas affected by drought (Burke and Brown, 2007). Also regional climate simulations highlight the Mediterranean region as being affected by more severe droughts, consistent with available global projections; (Giorgi*,* 2006 and Mariotti et al.*,* 2008). The precipitation concentration index (PCI) for the period (1960-2006), for example, has been studied in the Al Jazerah region (an area that includes 3 governorates in north-eastern Syria). Results show a severe decrease in annual rainfall of about 27.7% in Kamishli, 19.2% in Tel-Abiad and 26% in Hassakah. These variations are mainly related to the decreasing rainfall during winter and spring (Skaff and Masbate, 2010). The model-derived climate sensitivity of the Euphrates, Upper Tigris and Greater Zab river discharges (Smith et al. 2000) shows an increase (decrease) in precipitation by 25%, which raises (lowers) the discharge profile while keeping its distribution unchanged.

In addition, regional climate simulations project a reduction of rainfall in the mid-21st century of around 40-50 mm in the upper Euphrates and Tigris basin, which represents about 7 to 14 % of average rainfall. As a consequence, a drop of around 11% in the Euphrates River discharge is expected. Lehner et al. (2001) and EEA (2004) also estimated around 10 to 25% reduction in river runoff in the upper Euphrates and Tigris basin in 2070 versus 2000, which support the previous argument. Kitoh et al. (2008) presented even more pessimistic results in their projections of rainfall and stream-flow in the "Fertile Crescent" of the Middle East. Most studies found that the annual discharge of the Euphrates river will decrease significantly (29%–73%), as will the stream-flow in the Jordan River. A drier Mediterranean in 2031– 2060 translates into about one week of additional dry days along the coast and in the already dry southeast basin and over land areas in the northern part up to and over 3 weeks of additional dry days.

The region is subject to frequent agriculture (soil moisture) droughts and rainfed crops are strongly affected by fluctuations in precipitation. Especially the areas were annual rainfall ranges between 120/150 – 400 mm are considered moderately to severely vulnerable to drought (Erian et al., 2006).

Studies on long-term meteorological drought with the Standardized Precipitation-Evapotranspiration Index (SPEI) carried out by Erian et al. (2014) illustrate that droughts oscillated between relatively short cycles of drought and slightly wet to normal periods during the period 1961-1980. During the 1981-1990 decade, however, drought frequency increased gradually, with the year 1984 as a turning point.

As in the past, recurrent droughts forced people to abandon their rainfed fields. Recently, two severe drought cycles were recognized in Syria, the first one took place starting from the agriculture winter season of 1997/1998 until the agriculture season 2000/2001 and the second one started with the agriculture winter season of 2005/2006, lasting for five years. During the year 2008, around 1.3 million people (206,000 households) of a population of 22 million, almost 6% of the total population, have been severely affected by drought, out of which 800,000 have lost almost all their livelihoods and faced extreme hardship. This has crippled agriculture in eastern and north-eastern Syria; the livelihoods of the farmers who depend on only one crop were at risk as they had nothing else to support them and in some cases they migrated out of the affected areas; (Erian et al., 2011, Kattana, 2011 and UNISDR, 2011).

It was estimated that between 40,000 to 60,000 families migrated towards cities such as Aleppo, Damascus and Deir ez Zour or to Lebanon in search of work and for new sources of income (Nashawatii, 2011 and Erian, 2010).

FAO (2014a) summarized the main challenges facing Syrian agriculture and food security today, where around 6.3 million people are highly vulnerable to food insecurity and in critical need of food and agriculture support. The agricultural production declined due to the reduction of areas under cultivation, the adverse climatic conditions and the scarce investment made to protect and support the recovery of the agricultural sector. These factors – coupled with the decreased capacity of rural farming populations to generate income and access to food in highly affected areas – increasingly challenge food security. The significant drop in food production in Syria and disruptions in trade have also negatively affected food availability in neighbouring countries and heavily affected small-scale producers and workers along the supply chain of most agricultural commodities. Food price increases and removal of government subsidies have reduced the real income and purchasing power of poor households, forcing a change in dietary consumption and increasing malnutrition levels in host communities.

Following the above discussion, drought is to be considered an extremely serious problem. It will be an increasing threat for all countries that are already suffering from increasing conflicts, displacements and instability, alongside a growing fragility of ecosystem services, including trends of land degradation, soil depletion and reduced water security. Areas with a high sensitivity of the vegetation cover and crops to climate variability and change are at risk for political instability, due to the complexity of the shocks that might strike them. Besides Syria, also other examples like Darfur illustrate clearly the relation between increasing natural forces such as drought and land degradation and increasing political, social and economic pressures such as poverty, displacement, social vulnerability, violence and conflicts. They show how increased environmental hazards can accelerate instability. To overcome these effects there is a need to foster the interactions between natural and social sciences to help moving from crisis management to climate risk management.

### 4.2.4 California (Impact on groundwater resources and ecosystems)

From 2011 to 2015, California experienced the driest four successive winters in the instrumental record (since 1895) with the cumulative moisture deficit at almost a full year's precipitation. The 2014 and 2015 winters also set temperature records at 2 to 3 degrees Celsius above average. The lack of precipitation and high temperatures resulted in record-low snowpacks and exceptionally low flows in the state's rivers and streams. California's year-to-year variability derives primarily from the vagaries of its largest storms. In Southern California about 90% of year-to-year precipitation variability comes from inter-annual fluctuations in its wettest handfuls of days. This means that wet and dry years in California are opposite sides of the same coin. Drought in California occurs during years that are missing a few individual large storms and wet years occur when there are large-scale storms. Historically, dry California winters have most commonly been associated with a ridge off the west coast, part of a mid-latitude atmospheric wave train having no obvious SST forcing. Wet winters have most commonly been associated with a trough off the west coast and an El Niño event. According to the models, up to a third of California winter precipitation variance can be explained in terms of sea surface temperature (SST) forcing, with the majority explained by internal atmospheric variability. Nonetheless, SST-forcing was key to sustaining a system of high pressure over the west coast during each of the last three winters, and may have explained nearly one-third of the California's precipitation deficits during the recent drought. In 2011/12 the forced component was a response to a La Niña event whereas in 2012/13 and 2013/14 it was related to a warm tropical west Pacific SST anomaly. The ability to irrigate permanent crops with groundwater or marketed water will largely prevent the sector from more expensive fallowing of higher-valued crops and permanent crops. Some major conclusions of this event: Surface water shortages of nearly 10.7 million $m^3$ will be mostly offset by increased groundwater pumping of 7.4 million $m^3$. Groundwater offsets almost 70% of the drought water shortage. Water levels in over 40% of the wells in Southern California declined by almost 100 cm, in response to increasing stresses on groundwater sources in the region.

In California, extensive water infrastructure was built to serve multiple, often conflicting priorities, including delivery of water to agricultural and urban users and maintenance of ecological values. In the late summer and early fall of both 2014 and 2015 the lack of adequate surface flows led to sudden and unanticipated temperature increases in the Sacramento River and the death in both years of approximately 95 percent of the winter-run Chinook salmon populations, increasing the risks of extinction of this species (Broder 2015). This sudden ecological change was driven by a change in hydro-meteorological conditions when a temperature threshold was passed and by the failure of hydrologic models and water managers to anticipate the threshold or to act to prevent it. Estimates of impacts to agriculture exceeded US$40 billion (Howitt et al. 2015). As in other areas, such estimates do not include the cascading impacts of drought and water scarcity in other sectors nor the impacts on migrant workers. The 2011-2015 drought led to the very first groundwater management Act in California.

Additional recommendations for ameliorating future drought conditions include leveraging federal authority to resolve key water conflicts and align agency efforts and priorities; changing agricultural support programs to create watershed-scale benefits; improving headwaters management to protect water sources and reduce impacts of catastrophic wildfire; and modernizing weather, water and climate information to help all phases of planning and operations.

# 5 Drought Risk Management

## 5.1 Approaches to Drought Risk Management

While it is impossible to control the occurrence of droughts, the resulting impacts may be mitigated to a certain degree, namely through appropriate surveillance and management strategies that are pro-actively agreed and laid down in a Drought Management Plan.

The preparation of **Drought Management Plans** should be linked to an agreed conceptual framework for drought management and based on clear drought definitions. A starting point are the National Drought Management Policy Guidelines published by the **Integrated Drought Management Programme (IDMP)** (WMO and GWP 2014) and adapted to regional circumstances by the Global Water Partnership for Central and Eastern Europe (GWP-CEE 2015). As presented in EC (2007) two basic approaches for drought risk management are currently applied.

The **reactive** approach that is based on crisis management: it includes measures and actions after a drought event has started and is perceived. This approach is taken in emergency situations and often results in inefficient technical and economic solutions, because actions are taken with little time to evaluate best options and stakeholder participation is very limited. This approach has often been uncoordinated and untimely (Wilhite and Pulwarty, 2005). In addition, crisis management places little attention on trying to reduce drought impacts caused by future drought events.

On the other hand, the **proactive** approach is based on drought risk management: it includes appropriate measures being designed in advance, with related planning tools and stakeholder participation. The proactive approach is based on both short-term and long-term measures and includes monitoring systems for a timely warning of drought conditions, the identification of the most vulnerable part of the population and tailored measures to mitigate drought risk and improve preparedness. The proactive approach entails the planning of necessary measures to prevent or minimize drought impacts in advance. This approach has also been termed the three pillars of integrated drought management (Figure 20), advanced by Wilhite (WMO and GWP, 2014) and consists of i) drought monitoring and early warning systems; ii) vulnerability and impact assessment; and iii) drought preparedness, mitigation and response. It represents a common way of structuring the work toward and integrated approach to drought management (Pischke and Stefanski, 2018).

A **drought monitoring and early warning system (Pillar 1)** is the foundation of effective proactive drought policies to warn about impeding drought conditions. It identifies climate and water resources trends and detects the emergence or probability of occurrence and the likely severity of droughts and its impacts. Reliable information must be communicated in a timely manner to water and land managers, policy makers and the public through appropriate communication channels to trigger actions described in a drought management plan. That information, if used effectively, can be the basis for reducing vulnerability and improving mitigation and response capacities of people and systems at risk.

**Vulnerability and impact assessment (Pillar 2)** aims to determine the historical, current and, likely, future impacts associated with drought and to assess the vulnerability to these. Drought impact and vulnerability assessment aims to improve the understanding of both the natural and human processes associated with drought and the impacts that occur. The outcome of the vulnerability and impact assessment is a depiction of who and what is at risk and why.

The work related to **drought mitigation, preparedness and response (Pillar 3)** determines appropriate mitigation and response actions aimed at risk reduction, the identification of appropriate triggers to phase-in and phase-out mitigation actions, particularly short-term actions, during drought onset and termination and, finally, to identify agencies or ministries or organizations to develop and implement mitigation actions. Triggers are defined as specific values of an indicator or index that initiate and/or terminate responses or management actions by decision makers based upon existing guidelines or preparedness plans (WMO and GWP, 2016). Triggers should link indices or indicators to impacts that are occurring on the ground.

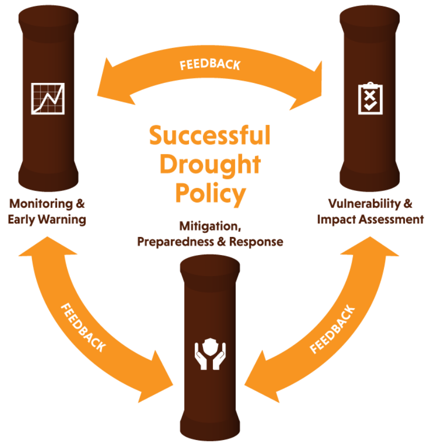



***Figure 20.*** *The three pillars of integrated drought management (After Pischke and Stefanski, 2018).*

In order to move from a reactive to a proactive approach, local or regional conditions must be taken in consideration, including the legislative and administrative framework as well as the natural conditions. An effective drought management plan should provide a dynamic framework for an ongoing set of actions to prepare for, and effectively respond to drought, including: periodic reviews of the achievements and priorities; readjustment of goals, means and resources; as well as strengthening institutional arrangements, planning, and policy-making mechanisms for drought mitigation (for instance, as depicted in EC, 2007).

A key decision support tool for crisis mitigation is embedded within the concept of early warning information systems. Efforts in drought early warning continue in countries such as Brazil, China, Hungary, India, Nigeria, South Africa, and the United States (Pulwarty and Sivakumar, 2015; Wilhite and Pulwarty 2017) and across Europe (Vogt et al. 2018). Regional drought monitoring activities exist or are also being developed in eastern and southern Africa and efforts are ongoing in West Asia and North Africa. An example of a global Drought Early Warning System is presented in Box 4. Research and experience in several watersheds show that several paradoxes in multistate water management and governance across borders can militate against the accurate assessment of socio-economic impacts and the effective use of scientific information for meeting short-term needs in reducing longer-term vulnerabilities. These lessons include an expanded use of incentives for improving collaboration, water-use efficiency, demand management and for the development of climate services to inform water-related management as new threats arise. Several cases show that changes in the management of climate-related risks (in this case "drought") may be most readily accomplished when: (1) a focusing event (climatic, legal, or social) occurs, creating widespread public awareness and opportunities for action; (2) leadership and the public, the so called "policy entrepreneurs", are engaged; and (3) a basis for integrating research and management is established (Pulwarty and Maia 2014; Wilhite and Pulwarty, 2017; Gleick, 2018). This latter dimension emphasizes the structure for developing the capacity to apply knowledge and to evaluate the consequences of actions amongst partners, to ensure the reliability and credibility of the projections of changes in the system outputs and to enable acceptable revisions on management practices in light of new information. Among others, examples of end-to-end information systems in which monitoring and forecasting, risk assessment and engagement of communities and sectors are aligned across the weather-climate continuum are exemplified by NIDIS (National Integrated Drought Information System) and the Famine Early Warning System Network

(FEWSNet) which provide coordination of diverse regional, national and local data and information for supporting planning and preparedness (Pulwarty and Verdin 2013). As a result of FEWSNet and efforts on the ground there have been successful cases of drought risk interventions to prevent humanitarian crises including the severe drought in Ethiopia in 2015-2016.

However, as noted in UNISDR (2011) drought remains a "hidden risk". The micro-level actions involving households, communities, and individual businesses are often underappreciated but, arguably, the most important elements of drought risk mitigation. WMO and GWP (2017) summarize several of these actions as follows:

- More secure land tenure and better access to electricity and agricultural extension were found to facilitate the adoption of drought risk mitigation practices among agricultural households in Bangladesh. Similarly, access to secure land tenure, markets, and credit played a major role in helping farmers cope with droughts in Morocco.
- Improved access to credit helped farming households in Ethiopia to cope better with drought impacts since they no longer needed to divest their productive assets. Moreover, since many rural households in Ethiopia tend to channel their savings into livestock, which may be wiped out during droughts, developing access to financial services and alternative savings mechanisms could also help to mitigate drought risk.
- Land use change and modification of cropping patterns are frequently cited as ways to build resilience against droughts.
- Diversification of livelihoods by adopting off-farm activities and divesting of livestock assets.
- A strong asset base and diversified risk management options are among the key characteristics of drought-resilient households in Kenya and Uganda. These aspects were due primarily to the households having better education and greater knowledge of coping actions against various hazards. This allowed them to diversify their income sources.

Although drought insurance is an effective and proactive measure, the development of formal drought insurance mechanisms is hindered in many developing countries by a number of obstacles, including high transaction costs, asymmetric information, and adverse selection (OECD 2016).

The experience of the JRC, IDMP, NIDIS, FEWSNet and other information and risk management systems illustrate that early warning represents a proactive social process whereby networks of organizations conduct collaborative analyses (see Pulwarty and Verdin, 2013). In this context, indicators help to identify when and where policy interventions are most needed and historical and institutional analyses help to identify the processes and entry points that need to be understood if vulnerability is to be reduced. Taking local knowledge and practices into account promotes mutual trust, acceptability, common understanding, and the community's sense of ownership and self-confidence (Dekens, 2007). As important as indicators are to such systems, it is also the governance context in which EWSs are embedded that needs further attention, since, particularly for people-centred strategies at the so-called "Last Mile", a mix of centralized and decentralized activities is required.

In the following sections recommendations are established for more effectively linking risk assessment approaches with resilience strategies that are applicable in practice and available to decision makers in a changing climate.

Drought events in the 21st century to some extent explain the emergence of several national and state initiatives centred on drought monitoring and preparedness, given that events of this magnitude have not motivated policy makers to act in the past. Widespread, severe, and multiyear droughts in countries or regions in recent years (e.g., Australia, U.S., Brazil, the Greater Horn of Africa, and Mexico) have been instrumental in moving the conversation on improving drought monitoring and preparedness forward. However, our experience would suggest that this is only one of the factors contributing to the increased attention to drought risk management in many drought-prone countries.

Early warning systems are more than scientific and technical instruments for forecasting hazards and issuing alerts. They should be understood as sources of scientifically credible, authoritative, and accessible knowledge that integrate information about and coming from areas of risk, thus facilitating decision-making (formal and informal) in a way that empowers vulnerable sectors and social groups to mitigate potential losses and damages from impending hazard events (Maskrey 2007, Seager et al. 2015).

## 5.2 Components of a Pro-active Drought Risk Management

Drawing on experiences form different countries, WMO and GWP (2014) presented and developed a set of guidelines to implement national level drought management policies. The purpose of these guidelines is to provide countries with a template of ten non-prescriptive steps that serve as a guideline for the development of drought management plans (Box 3).

***Box 3: Ten steps in the drought policy and preparedness process***

**Step 1:** Appoint a national drought management policy commission.

**Step 2:** State or define the goals and objectives of a risk-based national drought management policy.

**Step 3:** Seek stakeholder participation; define and resolve conflicts between key water use sectors, considering also transboundary implications.

**Step 4:** Inventory data and financial resources available and identify groups at risk.

**Step 5:** Prepare/write the key tenets of the national drought management policy and preparedness plans, including the following elements: monitoring, early warning and prediction; risk and impact assessment; and mitigation and response.

**Step 6:** Identify research needs and fill institutional gaps.

**Step 7:** Integrate science and policy aspects of drought management.

**Step 8:** Publicize the national drought management policy and preparedness plans and build public awareness and consensus.

**Step 9:** Develop education programmes for all age and stakeholder groups.

**Step 10:** Evaluate and revise national drought management policy and supporting preparedness plans.

*Source: WMO and GWP, 2014*

This 10-step process should modified and adapted to the local needs and experiences. At the macro level, for example, the GWP-CEE (2015, p.19) proposed for Central and Eastern European countries the following 7-step process for implementing effective drought management policies at the national level:

(1) Develop a drought policy and establish a drought committee.
(2) Define the objectives of a drought risk-based management.
(3) Make an inventory of data needs and available data for developing a Drought Management Plan.
(4) Produce/update the Drought Management Plan.
(5) Publicize the Drought Management Plan for public involvement.
(6) Develop scientific and research programmes.
(7) Develop educational programmes.

With regard to the practical preparation, implementation and follow-up of a Drought Management Plan at the local level (river basin, department, town) the following (adaptable) seven steps (schematically presented in Figure 21), provide an example of a possible implementation and updating of a Drought Management Plan as indicated in step 4 above (based on GWP-CEE, 2015):

(1) Characterise regional droughts based on the evaluation of historical drought events. Incorporate suitable drought indicators that best fit the hydro-climatology of the locality.
(2) Identify indicators and thresholds for the classification of the different drought stages (onset, peak, amelioration and end). Relevant variables to define drought impacts should be adjusted for every season and region depending on the main economic sectors involved and intrinsic characteristics of the river basins.
(3) Implement a drought early warning system (EWS). Implementation of a EWS requires developing, testing, and producing monitoring and forecasting information as well as a system to timely disseminate the relevant information to the key stakeholders (Werner et al. 2015). Because decision-makers require accurate early warning information to implement effective drought policies and response and recovery programmes, this component is essential for drought risk management and illustrates an important connection between risk and crisis management (Wilhite and Buchanan-Smith, 2005).
(4) Develop a programme of measures for prevention and mitigation of droughts. A detailed list of potential measures to take should be available for the main stakeholders (e.g. practicality of insurance products, early warning systems, reservoir improvements). The emphasis on drought planning is fundamental to drought risk management at any decision-making level. Incorporating planning will help decision-makers to prepare for multiple hazards, including drought and climate change, leading to greater economic and societal security at all levels (GSA, 2007).
(5) Update and follow-up of the drought management plan. Assets exposed as well as characteristics of droughts change with time. For instance, an increasing population or relocations, increasing crop areas, mainly in marginal zones, or even the local effects of climate change can reshape the drought risk within a few years.
(6) Develop a water supply plan, providing specific information on the existing water supply infrastructure and groundwater resources.

(7) Assess the implications of prolonged droughts. Long droughts lead to unprecedented damages, mainly by exhausting water storages and groundwater. Specific restrictions on water use may apply for water allocation, for irrigation or even for human consumption.

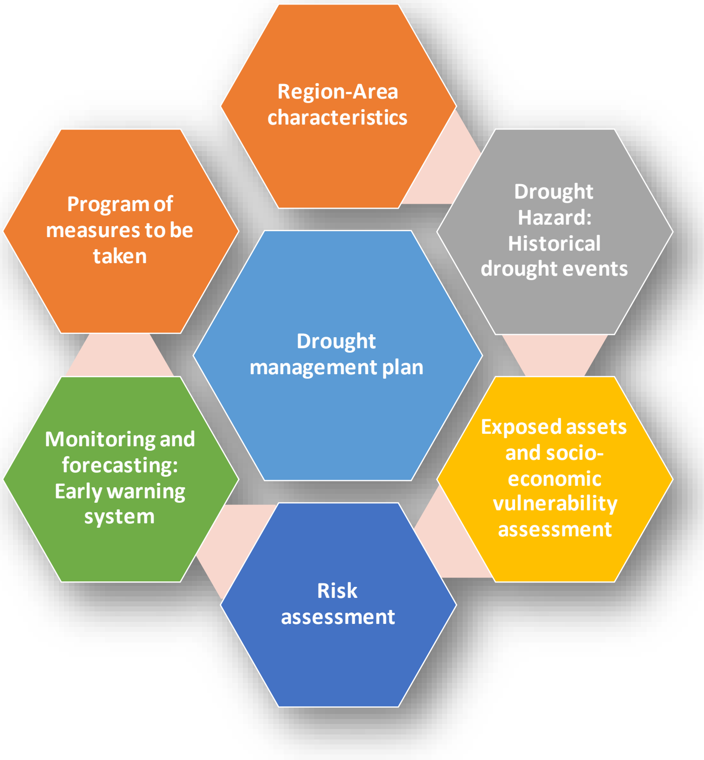



***Figure 21.*** *Elements of a Drought Management Plan. Based on: Global Water Partnership Central and Eastern Europe (GWP-CEE, 2015).*

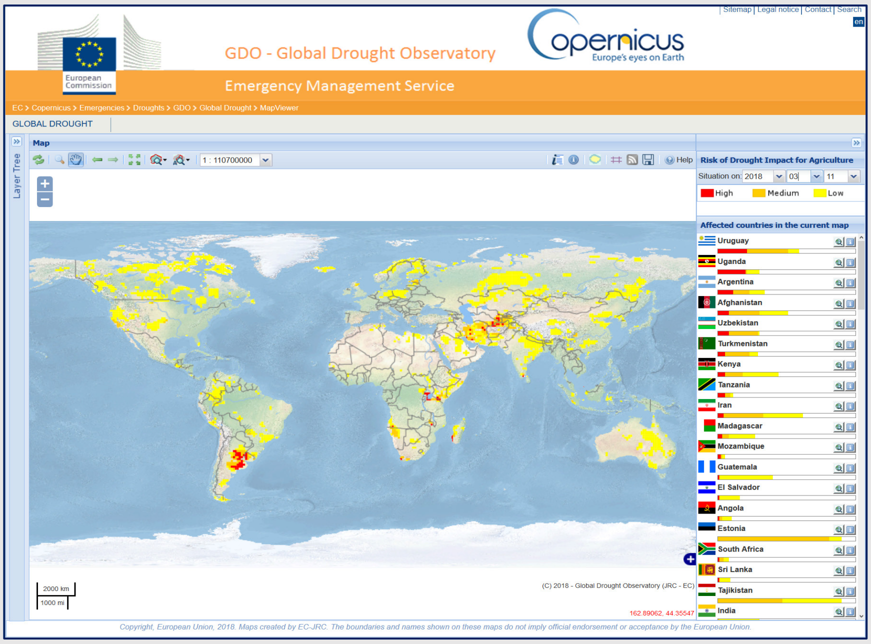
The need for a framework in the form of a policy that combines different approaches that have been considered key in moving from a crisis management approach to a proactive risk management approach has led to the launch of the **Integrated Drought Management Programme (IDMP, www.droughtmanagement.info)** by the WMO and the GWP in 2013. The objective of the IDMP is to support stakeholders at all levels by providing policy and management guidance and by sharing scientific information, knowledge and best practice for an integrated approach to drought management.

The strength of IDMP is to leverage activities of its various partners to determine the status and needs of countries and to move forward collectively to address these needs. The IDMP also uses the network of National Meteorological and Hydrological Services (NMHSs) and related institutions affiliated with WMO and the Regional and Country Water Partnerships of the GWP as a multi-stakeholder platform to bring together actors from government, civil society, the private sector and academia working on water resources management, agriculture and energy.

## *Box 4: The Global Drought Observatory (GDO)*

Coordinated monitoring and forecasting of user oriented drought indices is crucial for drought risk management and information exchange across borders. Cross-border Early Warning Systems (EWS) are one of the pillars for a proactive risk management.

One of the major challenges in EWS relates to linking drought severity with drought impacts in the variety of economic, social and environmental sectors. The **Global Drought Observatory (GDO)**, developed by the European Commissions' JRC for the European Union Emergency Response Coordination Centre (ERCC), includes sector-specific exposure and vulnerability information for assessing the Risk of Drought Impact (RDrI) in different sectors. The GDO landing page presents a global map of the RDrI for the agricultural sector (RDrI-Agri), together with a hierarchical list of all affected countries visible in the map. Various tools and information layers allow for an in-depth analysis of the situation for sub-national administrative units and for the semi-automatic creation of Analysis Reports. Since January 2018 GDO is part of the Copernicus Emergency Management Service (EMS).




**The Global Drought Observatory (GDO).**

Example of the Risk of Drought Impact Indicator for Agriculture (RDrI-Agri) for the period 11 to 20 March 2018. Source: GDO (2018)

*http://edo.jrc.ec.europa.eu/gdo*

## 5.3 Benefits of Action against Costs of Inaction

There are currently only a limited number of tested strategies available by which to identify appropriate drought risk-reduction strategies. Demonstration of effective mitigation approaches and preparedness plans as well as success stories are, however, essential to foster the buy-in to similar efforts by policymakers, scientists, media, and the general public (UNISDR, 2006).

The costs of pro-active drought management are usually lower than the costs of inaction, and can generate significant economic benefits. The US Multihazard Mitigation Council (2005), for example, estimated that every dollar spent by the Federal Emergency Management Agency (FEMA) on natural hazard mitigation provides the country with approximately US$ 4 in future benefits, while particularly for droughts, the country would save at least US$ 2 on future disaster costs from every US$ 1 spent on drought risk mitigation (Logar and van den Bergh, 2013). Related actions to mitigate drought impacts include more secure tenure, better access to electricity, improved access to credits, land use change and modification of cropping patterns, taking better advantage of groundwater resources and adopting off-farm activities to diversify livelihoods (WMO and GWP, 2017).

Drought risk management can have substantial socio-economic co-benefits, since some of the related actions build not only resilience against droughts but also against additional socio-economic and environmental shocks. Better access to electricity, agricultural extension, off-farm activities and higher education, for example, that are associated with stronger resilience to drought shocks were identified as factors that also help address land degradation, facilitate poverty reduction and improve household food security (WMO and GWP, 2017).

In general terms and at the international level, the economics of drought risk management encompass a broad spectrum of targeted activities, including:

1) The development of innovative market based insurance solutions to be promoted in cooperation with national governments.
2) The promotion and support of investments in drought resilient infrastructures.
3) The promotion of knowledge transfer and capacity building.
4) The development of initiatives to integrate drought risk management considerations into the international financial system.
5) The integration of drought risk management concepts into international laws and regulations.

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## 5.4 Adaptation and strengthening resilience

Considering the expected aggravation of drought frequency and intensity under climate change, adaptation to these changes is of high importance for increasing the resilience of affected societies. Countries suffering from increasing drought intensity, frequency and duration are likely to suffer more drought-related impacts such as losses in agricultural production and rural livelihoods, increased migration, reduction of available public water supply, losses in other economic sectors as well as ecosystem decline. Following Erian et al. (2014), they are in need to:

1) Strengthen commitments for comprehensive disaster risk reduction through the implementation of climate change adaptation (CCA) and disaster risk reduction (DRR) strategies in national policies, legal frameworks, development plans and actions. Through the development of decentralized resources and community participation. Through the development of capacities to identify, assess and monitor drought risks in national/local multi-hazard risk and vulnerability assessments. Through building of capacities/systems to monitor, archive, and disseminate data and through the development of regional early warning systems and networks.
2) Build resilience through knowledge, advocacy, research and trainings by making information on drought risk accessible to all stakeholders; through educational material, curricula, and public awareness; through citizen engagement and behavioural change.
3) Integrate disaster risk reduction into emergency response, preparedness and recovery by making preparedness and contingency plans; by fostering recovery and reconstruction activities inclusive of all society groups and at all administrative levels; by allocating budget locally for emergencies; and by fostering coordination between national and local entities for timely information exchange during hazardous events and disasters.
4) Integrate activities in the national strategy for CCA and DRR, including: drought risk loss insurance; improved water use efficiency; reduction of water leakages from the distribution networks; use of regenerated water; use of desalinized water from the sea based on renewable energies; adopting and adapting existing water harvesting techniques; conjunctive use of surface and groundwater; upgrading irrigation practices on both the farm level and on the delivery side; developing crops tolerant to salinity and heat stress; changing of cropping patterns; altering the timing or location of cropping activities; diversifying production systems into higher value and more efficient water use options; capacity building of relevant stakeholders.
5) In preparing for future droughts, work plans should include several major activities:
   - Mapping and monitoring drought risk,
   - Mapping and modelling the long-term impacts on land degradation,
   - Development of drought adaptation and action plans at local level (e.g. municipalities),
   - Identifying hot spots and socio-economic vulnerabilities in different sectors,
   - Preparing global and regional reports that assess drought impacts on the water, food and social vulnerability nexus,
   - Implementing pilot activities for risk management.

# 6 The Way Forward

A great deal of reliable knowledge on reactive and anticipatory approaches to drought hazards and disasters has been derived over the past one hundred years. However, in an increasingly interconnected and rapidly changing world, several areas of concern for drought risk management are emerging. We highlight the following areas of concern and opportunity:

**1. Risk assessment (sectorial and multi-hazard)**

Assessing the risk for drought-related impacts to society and environment is a difficult task, complicated by the creeping nature of the phenomenon, its often large spatial extent and temporal duration, leading to cascading impacts that may affect areas far distant from the actual drought and may last long after the actual drought has ceased. Missing standardized data on past impacts (both damage and loss) are a further complication. Finally, the interlinkages with other hazards such as wildfires, heatwaves and even floods and the combined risks arising from different hazards need to be explored. These risk assessments need to be sector specific, requiring an adequate set of environmental and socio-economic data related to the respective sectors.

**2. Uncertainties associated with a changing climate and its manifestation at regional and local levels**

There is a strong need to approach climate model outputs far more critically than at present, especially for impact assessment to support adaptation at the local level. Many hotspots that show fragility in the face of climate change also exhibit soil moisture and soil quality reduction combined with reduced adaptive capacity. Scenario planning (based on past, present, and projected events) may provide better understanding of whether and how best to use probabilistic information with past data and cumulative risks across climate timescales. Central to all of the above is a sustained network of high-quality monitoring systems.

**3. The increasingly complex pathways through which drought impacts filter: Water-Energy-Food nexus**

The United Nations (FAO, 2014b) describe the water-energy-food nexus as follows: "Water, energy, and food are inextricably linked. Water is an input for producing agricultural goods in the fields and along the entire agro-food supply chain." Agriculture is currently the largest user of water at the global level, accounting for 70 percent of total withdrawal. At the same time, the food production and supply chain accounts for about 30 percent of total global energy consumption. Energy is required to produce and distribute water and food, to pump water from groundwater or surface water sources, to power irrigation systems, and to process, store, and transport agricultural goods. Global demand for energy is expected to increase by 400 percent by 2050. In areas where hydropower plays a significant role in national energy supply, such as Brazil and Zambia, blackouts and jumps in energy prices have occurred during extended periods of drought. Similarly, in 2014 as a result of low flows, the Glen Canyon Dam (Colorado River) had to purchase US$60 million of thermal power to offset market demands in the US Southwest, the fastest growing region in the country. Since the 1990s, average increases in the yields of maize, rice, and wheat at global levels have begun to level off at just about 1 percent per annum (FAO, 2017). There are many synergies and trade-offs between water, energy use, and food production. Increasing irrigation might promote food or biofuel production, but it can also reduce river flows and hydropower potential through increased overall water withdrawals and, thus, jeopardize food security. In most cases, each component has been studied and managed individually, without consideration of the trade-offs, cultural similarities (and differences), interactions, and complementarity for jointly ensuring water, energy, and food security.

## 4. The costs of drought impacts and the benefits of action and costs of inaction

The major assumption behind proactive action around drought is that present or upfront actions and investments can produce significant future benefits. No comprehensive study exists for drought. WMO and GWP (2017) have outlined some of the advances to date in assessing benefits of action and the costs of inaction. In the area of drought and other hazards, much more work needs to be done to realize what has been called the "triple dividend of resilience" (Tanner et al. 2015).

These benefits include:

a. Avoiding losses when disasters strike
b. Stimulating economic activity thanks to reduced disaster risk
c. Developing co-benefits, or uses, of a specific disaster risk management investment

## 5. The role of technology, efficiency and policy

Since 1980, water use in the United States has returned to 1970 levels of use. During this period, the US population increased by 33 percent. This transformation illustrates the cumulative effectiveness of behavioural and efficiency changes. However, the major drivers were national policies reducing average annual demand and freshwater withdrawals in the United States, demonstrating the value of enabling legislation and regulation in leading to conservation measures. These included the Clean Water Act (1972), National Environmental Policy Act (1970), Endangered Species Act (1973), and Safe Drinking Water Act (1974). According to Stakhiv et al. (2016), these acts fostered and secured a bottom-up enabling institutional framework that focused on regulating, monitoring, and enforcing a suite of water quality and environmental laws that passed in the 1970s.

## 6. Links to human security and conflict: an area for future research

Hydroclimatic variability can pose an important threat to human security through impacts on economies and livelihoods, independent of the conflict pathway (Kallis and Zografos 2014). There is increasing agreement in research regarding links between climate and conflict. The connection, however, is complex. While water scarcity and food insecurity have been shown to play roles in dislocation and unstable conditions, little is known about the strength of those relationships (Erian et al. 2010). Researchers and practitioners are still grappling with how to ascertain specific drivers in ways that inform deliberate action. The pathways to insecurity outlined in this report include several drought-sensitive issues, such as:

- Adverse effects on food prices and availability
- Increased risks to human health
- Negative impacts on investments and economic competitiveness

The need to explicitly acknowledge differing social values, to strengthen institutional mechanisms for collaboration, and to collect standardized data on drought impacts as a basis for reducing vulnerability and enhancing resilience needs to be acknowledged. How drought and climate change may play into future fragility will be an area of increasing research and security interest.

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## List of abbreviations

| | |
|---|---|
| CCA | Climate Change Adaptation |
| CDI | Combined Drought Indicator |
| ERCC | Emergency Response Coordination Centre |
| EWS | Early Warning System |
| DDR | Disaster Risk Reduction |
| IDMP | Integrated Drought Management Programme |
| IPCC | Intergovernmental Panel on Climate Change |
| JRC | Joint Research Centre |
| FEWSNET | Famine Early Warning System Network |
| GDO | Global Drought Observatory |
| GHSL | Global Human Settlement Layer |
| GWP | Global Water Partnership |
| NMHS | National Meteorological and Hydrological Services |
| RCP | Representative Concentration Pathways |
| SPEI | Standardised Precipitation Evapotranspiration Index |
| SPI | Standardised Precipitation Index |
| UNISDR | United Nations International Strategy for Disaster Reduction |
| WMO | World Meteorological Organization |

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