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Effects of droughts on health: Diagnosis, repercussion, and adaptation in vulnerable regions under climate change. Challenges for future research

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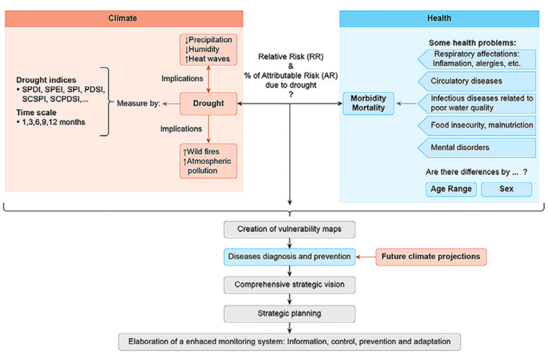
GRAPHICAL ABSTRACT



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ABSTRACT

There is little doubt about the effects of drought events on human health in the present climate. Projections of climate change indicate an increase in the occurrence and severity of droughts in the 21st century in a number of regions, thus it is likely that these types of hydrological extremes could have more of an impact if appropriate adaptation measures are not taken. The majority of studies on the effects of drought are focused on meteorological, agricultural, or hydrological contexts, but there are rather fewer assessments of the impacts of droughts on health. In particular, there have been hardly any attempts to compare different drought indices in order to identify and quantify the impacts of drought on health systems. In addition, rather better knowledge is needed on the mechanisms of vulnerability involved. In this paper, we attempt to describe the complexity of drought phenomena and the difficulty involved in quantifying the health risks linked to their occurrence. From an international perspective, we provide a brief review of the harmful effects of droughts on health in the context of climate change, as well as the vulnerability factors related to droughts. We make an assessment of aspects that have not yet been investigated, or which require further attention to be devoted to this topic. The principal aim of this paper is therefore to draw attention to the need to consider closely the relationship between drought indices and human health, in order to achieve a more fundamental understanding, and to propose specific courses or lines of action for future years, which could eventually be of use to healthcare providers and services.

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1. Difficulty in studying drought events and quantifying their risks on human health

1.1. Difficulty in defining and characterizing "drought"

Unlike other extreme phenomena, droughts are highly complex events that are difficult to define clearly and quantify (Vicente-Serrano et al., 2012; Quiring, 2015; Vicente-Serrano, 2016; Spinoni et al., 2019) because it is difficult to establish a beginning and an end of each event and many of the definitions depend on the different disciplinary perspectives or systems in which it is analysed (Wilhite, 2000; Valiente, 2001; Vicente-Serrano et al., 2012). Thus, different types of droughts can be distinguished, creating new challenges in the estimation of health risks because each type of drought can affect health outcomes in different ways (Berman et al., 2017). Standard classifications refer to meteorological, agricultural, hydrological, and socioeconomic droughts that include specific-sector impacts in their definitions (Wilhite, 2000; Mishra and Singh, 2010; Dai, 2011; Stanke et al., 2013; Sena et al., 2014; Ebi and Bowen, 2016; MINECO, 2019):

- **Meteorological drought** is a consequence of the prolonged deficit of precipitation or an acute shortage of precipitation, and it usually affects large areas. Its occurrence is determined by parameters such as the duration, severity, and intensity and it gives rise to other types of drought.
- **Hydrological drought** is associated with the impacts of precipitation shortages on surface water or groundwater supplies (discharge deficit).
- **Agricultural drought** links the characteristics of meteorological and hydrological drought to agricultural impacts. It refers to a deficiency in soil moisture to satisfice particular crop needs.
- **Socioeconomic drought** is based on the excess demand with respect to the supply for a specific economic good as a consequence of a water shortage that affects people.

The different types of droughts are not independent because they are associated with a deficiency in the hydrological variable characteristic; hence, drought concepts should be understood in an interdisciplinary pathway as socio-environmental phenomena that are produced by mixtures of climatic, hydrological, environmental, socioeconomic, and cultural factors (see Kallis, 2008). Particularly, we considered drought as a complex, recurrent and slow natural extreme climatic event that affects several environmental and society systems, whose effects depend on the vulnerability factors such as the magnitude of the events, geographical location of the affected region, socioeconomic and demographic aspects of exposed population as well as the sensibility and adaptive capacity of the communities, among others. This phenomenon acts in different spaces and time scales, and occurs as a consequence of a deficit in the amount of rainfall over a long period (several months to years) being largely influenced by the demands of human and environment use of water. The severity of the event depends on the duration, intensity and geographical extent and can be aggravated by the influence of other climatic factors such as high temperatures, strong winds or low relative humidity (Wilhite, 2000; Wilhite et al., 2007; Kallis, 2008; Quiring, 2015).

1.2. Metric of droughts and the estimation of risks. The crucial role of drought indices

Droughts are slow creeping phenomena, and many of their impacts are indirect, non-structural, diffuse, and often accumulate slowly over time and may linger after the end of an event, making it challenging to study as discrete events (Wilhite, 2000; Kallis, 2008; Mishra and Singh, 2010; Brüntrup and Tsegai, 2017; Spinoni et al., 2019). Furthermore, the different effects largely depend on the magnitude of drought events (Stanke et al., 2013; Ebi and Bowen, 2016). Drought indicators are essential in monitoring the hydrological extremes, as well as detecting and quantifying the direct and indirect risks associated with the occurrence of these hazards to obtain better knowledge and preparation to tackle drought impacts (Vicente-Serrano et al., 2017). Although numerous specialized indices have been proposed for measuring different forms of drought (Keyantash and Dracup, 2002; Bachmair et al., 2016; WMO and GWP, 2016), there is a lack of studies that focus on examining which index is the most accurate for measuring the type of drought with reference to its effects on health, which is of critical importance (Bachmair et al., 2016; Berman et al., 2017; Salvador et al., 2019), and there is no specific index designed specifically for address this purpose (Berman et al., 2017). As different effects of droughts can vary in both space and time (Wilhite et al., 2007; Salvador et al., 2019), several indices are widely used in the scientific literature, such as the Standardized Precipitation Index (SPI) and Standardized Precipitation Evapotranspiration Index (SPEI), which have the advantage of being able to be used with different time scales. SPI is calculated based on precipitation data, while SPEI is based on precipitation and evapotranspiration data, taking into account the atmospheric evaporative demand (Vicente-Serrano et al., 2012). Another index commonly used in drought analysis is the Palmer Drought Severity Index (PDSI) (Palmer, 1965; Dai, 2011) that could be used individually or in combination with other different types of drought indicators to create new indices as those used by the United States Drought Monitor (USDM), which was recently used to monitoring drought conditions and estimating the risk of hospital admissions and mortality in USA (Berman et al., 2017). On the other hand, PDSI has been modified with serval aims into derived indicators as for instance the Standardized Palmer Drought Index (SPDI) (Ma et al., 2013), Self-Calibrating PDSI (SCPDSI, Wells et al. (2004)), or the modified Palmer Drought Severity Index (MPDSI, Yu et al., 2019). The different scales used for some of these indices reflect the quantity of water deficits during different periods of accumulation, which allows association with the different forms of droughts: one month of accumulation is used for meteorological droughts, one to six months is used for agricultural droughts, and six to 24 months or longer is used for hydrological droughts (Vicente Serrano, 2016; Monteiro et al., 2019), and used for the first time in Salvador et al. (2019) linked to health affectations.

2. Climate change-drought-health nexus: a global overview

Climate change is one of the most substantial environmental challenges worldwide and is in large part caused by anthropogenic activities, which increase greenhouse gas emissions that actively contribute to global warming (Franchini and Mannucci, 2015). It has been widely described that a consequence of climate change would be an increased frequency in extreme climatic events such as heatwaves, droughts, floods, cyclones, and forest fires that would have a higher intensity, leading to far-reaching effects on environmental and human systems (IPCC, 2014; Watts et al., 2015; Bell et al., 2018; Gupta et al., 2019).

Among the different climatic extremes, droughts are widely considered as the costliest, most complex and destructive phenomena, as well as the least understood event affecting more people than any other climatic hazard (Obasi, 1994; Wilhite, 2000; Kallis, 2008). There is a growing body of evidence to indicate that health is profoundly vulnerable to droughts (Stanke et al., 2013; IPCC, 2014), which affect several million people every year (Dai, 2011), and are responsible for widespread morbidity and mortality worldwide (Stanke et al., 2013). As much as 15% of natural disasters globally are caused by droughts and the mortality related to droughts represents around 59% of the total deaths caused by extreme weather events (McCann et al., 2011). In addition, it was described that 15 of the major droughts in 2003 to 2012 affected around 36.5 million people worldwide (Ebi and Bowen, 2016). There are differences in the repercussions and magnitude of drought impacts in the different continents because the resource-poor nations are where most of the drought-related morbidity and mortality occur, and the resource-rich nations have a mainly economic impact (Keim, 2015). A higher number of people are affected by droughts in Asia, while Africa is where more drought disasters and higher mortality occur, and the West suffers higher economic damages (Kallis, 2008). Droughts in the United States have caused mounting costs (an average of $6–8 billion has been reported) (Keyantash and Dracup, 2002). Furthermore, in Europe where occurs an increase in the number and severity of droughts since 1980, the cost is estimating in around €100 billion during the past 30 years (European Commission, 2010). A global analysis (Alpino et al., 2016) shows that from 659 droughts studied during 1900–2005, they resulted in 2.21 billion people affected and 11 million deaths in the world as well as in notable economic losses in several regions such as in China (around 2.4 billion dollars) or Brazil (around 11 billion dollars).

The continued deficiency of precipitation and water shortage over an extended period promotes the occurrence of drought events (McCann et al., 2011; Stanke et al., 2013; Quiring, 2015). However, other climatic factors can escalate the intensity and aggravate drought periods, such as the increase in temperatures (as a result of the loss of water by evapotranspiration) (Kallis, 2008; Vicente-Serrano et al., 2014), high winds, or low relative humidity (Wilhite, 2000; Quiring, 2015). Anthropological activities and inefficiencies in water distribution, planning, and management (eg. poor land management, deforestation, soil degradation, water mismanagement policies) can induce or potentially exacerbate the severity of droughts and their effects, whose consequences could be aggravated by the occurrence of droughts as well (Quiring, 2015; Brüntrup and Tsegai, 2017; Spinoni et al., 2018; Gebremeskel et al., 2019). In this aspect, although droughts are understood as natural phenomena, mismanagement of water resources can lead to increase in drought susceptibility, greater water scarcity intensification, drier soils, overexploitation of groundwater reservoirs, higher risk of forest fires occurrence, as well as other environmental and social costs, which in consequence can in turn to strengthen the negative effects associated to droughts (e.g. Brüntrup and Tsegai, 2017). Thus, is crucial importance that government systems pay particular attention to implement good measures of water management, and promote the establishment of good systems of surveillance being necessary a responsible use of water.

Droughts appear to be increasing in both developing and developed countries (Quiring, 2015) and the Intergovernmental Panel on Climate Change (IPCC) reports indicate that the health impacts of climatic extremes, such as droughts, may be reduced but not eliminated in more developed countries and there will be a heterogeneous response based on socioeconomic means and underlying health status (IPCC, 2014). In this context, future projections of climate change indicate that droughts will become more frequent and intense over the 21st century as a result of reduced precipitation and increased evapotranspiration in several regions in the world (WHO, 2018). This may especially impact Southern Europe, the Mediterranean region, Central Europe, Central North America, Central America and Mexico, northeast Brazil, and Southern Africa (Vicente-Serrano et al., 2011; Ebi and Bowen, 2016), which could further reinforce any dangers to public health, especially in vulnerable regions. Particularly, it has been estimated that about half of the world's population will live in conditions of water scarcity by 2025, which will compromise water quality; this is already evident in different parts of the world (Bifulco and Ranieri, 2017). Furthermore, a study conducted in Europe projected in the next decades an increase in the frequency of droughts mainly in spring and summer (especially over southern Europe) but also a decrease in the frequency of droughts over Northern Europe in winter (Spinoni et al., 2018).

3. Direct and indirect effects of drought on health and vulnerability

3.1. Direct and indirect effects of droughts

Droughts have far-reaching effects that are both short and long term across diverse sectors (environmental, economic and social). However, the classification of the effects in short or long term impacts is usually very complex (Wilhite, 2000; Hayes, 2002; Keyantash and Dracup, 2002; Wilhite et al., 2007; Alpino et al., 2016; Bachmair et al., 2016). In terms of health, several compressive reviews on health risks associated with droughts indicated that drought effects occur primarily through an indirect pathway (Stanke et al., 2013; Sena et al., 2014; Yusa et al., 2015; Ebi and Bowen, 2016).

In a direct pathway, droughts impact the environment and ecosystems through a reduction in water availability and quality, decrease of hydropower production, diminution of food production, or an increase in forest fires and wildlife damages (Wilhite et al., 2007; Stanke et al., 2013; IPCC, 2014; Bachmair et al., 2016; Bifulco and Ranieri, 2017). Droughts can also incorporate and reflect the effects of other associated extreme climatic events to negatively affect health when they take place in the same period because concurrent incidence can accelerate the development of droughts and increase indirect risks on health (Stanke et al., 2013; Bell et al., 2018; Salvador et al., 2019). During summer droughts may be strongly associated with the increase of heatwaves, and stagnation conditions (e.g. prolonged blocking of anticyclonic atmospheric conditions) (García-Herrera et al., 2010), which favour the increase in pollutant concentrations associated with stagnant conditions (e.g. Wang et al., 2017). In winter, it has been described that droughts can generate unfavourable dispersion conditions and much higher particulate matter (PM) with harmful effects on health (e.g. Hu et al., 2019). On the other hand, droughts can also induce extreme temperatures through variations in soil moisture (e.g. He et al., 2014). In addition, heatwaves may increase the severity of droughts, and both events may directly promote an increase in the frequency and intensity of wildfires that release toxic aerosols into the atmosphere (He et al., 2014; IPCC, 2014; Franchini and Mannucci, 2015). However, the mechanisms between these phenomena are complex and can occur without the presence of droughts.

In any way, the majority of health impacts that are linked to droughts are primarily indirect (Ebi and Bowen, 2016). In the case of the most visible impacts, a combination of drought events with extreme precipitation can compromise the availability and quality of water (microbiological and chemical contamination) and indirectly lead to an increased risk for infectious illnesses, particularly water-, food-, zoonotic-, and vector-borne diseases affecting the security of the population (Hayes, 2002; Tirado-Blazquez, 2010; Yusa et al., 2015; Alpino et al., 2016; Bell et al., 2018). Several studies have indicated an association between the incidence of droughts (as the reduction in water levels, streamflow, and the consequent stagnation) and various waterborne diseases transmitted through faecal-oral pathways caused by bacterium and other pathogens (e.g. *Escherichia coli, Salmonella, Vibrio cholerae*), triggering diarrheal illness and gastrointestinal disorders and other water-related diseases, which could threaten public he (Bifulco and Ranieri, 2017; Bell et al., 2018). In addition, the incidence of high temperatures and drought conditions could also promote massive blooms of toxin-producing cyanobacteria (Yusa et al., 2015; Lehman et al., 2016; Walter et al., 2018).

Droughts have also been strongly linked to food insecurity (undernutrition and malnutrition) (Watts et al., 2017) through a reduction in the quantity and stability of food, as well as through affectation of water quality and quantity, which lead to an increased risk of impairing the immune system (Lohmann and Lechtenfeld, 2015), as well as morbidity and mortality (Ebi et al., 2010; Stanke et al., 2013; IPCC, 2014; Ebi and Bowen, 2016).

Other drought-related risk on health is a rise in the incidence of vector-borne diseases (Brown et al., 2014; IPCC, 2014; Alpino et al., 2016). In some extratropical regions across Europe and North America, vector-borne diseases can be promoted by climate change (increased temperatures and drier conditions) because of their geographic location, when climatic conditions are similar to those found in tropical regions where vector-borne diseases are endemic (López-Vélez and Molina Moreno, 2005). In this context, droughts also have impacts from wildlife intrusion, rodents, and pests that may cause an increase of harmful affectations to the human population (Hayes, 2002).

As stated above, droughts have frequently been associated with drier soil, deforestation, an increase in airborne dust, wildfire smoke and poor air quality (increased toxic particles in the atmosphere), as well as alterations in the dispersion of allergens, which potentially compromise respiratory and circulatory health (Stanke et al., 2013; IPCC, 2014; Sena et al., 2014; Yusa et al., 2015; Berman et al., 2017; Wang et al., 2017; Bell et al., 2018). These affectations may result in mortality, especially among vulnerable populations such as the elderly and people with pre-existing chronic problems (Hayes, 2002; Watts et al., 2017; Bell et al., 2018; Salvador et al., 2019). A recent study conducted in the Western USA during 2000 to 2013 described that high-severity and worsening drought conditions increased the risk of mortality, but were also linked to a decrease in respiratory admissions among older adults (Berman et al., 2017), in contrast to evidence of other studies (Smith et al., 2014; Salvador et al., 2019). Furthermore, it was found more significant repercussions on the risk for cardiovascular diseases and mortality in those regions that had previously been less exposed to drought events (Berman et al., 2017). For the first time, a recent study conducted by Salvador et al. (2019) in NW Iberian Peninsula (Southern Europe) showed the significant association between the effect of droughts, measured by two daily drought indices (SPI and SPEI) at different accumulation periods and daily mortality (natural, respiratory, and circulatory causes) during a long period from 1983 to 2013. The main findings suggested that interior regions were the most affected principally for shorter droughts (in comparison with coastal areas), where impacts on daily mortality were mainly explained by the effects of atmospheric pollution, and the results for both indices used were very similar.

But, in this way, the study by Vicente-Serrano et al. (2012) shows that although SPEI and SPI showed similar results, SPEI is the best measure for detecting drought effects on hydrological, agricultural and ecological variables particularly in summer. So, and according to the global warming projections, SPEI could also provide a better estimation for droughts severity and health risks than SPI, for bigger areas, because the former considers both precipitation and evapotranspiration data for its calculation, while SPI only takes into account precipitation data.

Finally, the effects of droughts on mental health and wellbeing is a crucial and far-reaching issue. Prolonged droughts are associated with socioeconomic losses, forced displacement of communities (Wilhite et al., 2007; Alpino et al., 2016), which can lead to serious mental health problems and emotional consequences such as chronic stress, distress, worry, sleeplessness, generalized anxiety, depression, conflict and violence (Hayes, 2002; Sartore et al., 2007; Berry et al., 2010; Shukla, 2013; Stanke et al., 2013; Vins et al., 2015). Other studies have also indicated that, in extreme cases, prolonged droughts have been associated with an increase in the rate of mortality by suicide, mainly in rural populations (Shukla, 2013; IPCC, 2014; Obrien et al., 2014; Berman et al., 2017). Further, there are discussions about the role of extreme drought conditions as a contributing factor in civil conflicts (Selby et al., 2017), political instability and crises (Bell et al., 2018).

Many of these relationships were summarized in Fig. 1, trying to sum up the link between climate, droughts, human health, environmental, and socioeconomics problems.

3.2. Drought vulnerability climate change

Vulnerability mediates the hazards and impacts and is a function of drought exposure and the sensibility and adaptive capacity of the population (Kallis, 2008; Ebi and Bowen, 2016). The vulnerability is also determined by demographic characteristics, technologies, policies, and social behaviours (Quiring, 2015). Several studies indicated that the negative effects of droughts are in line to the level of development and degree of preparation of different countries in adapting their systems to current and future climatic variability in different sectors. Socioeconomic factors, the underlying health status of the population, geographical location, and the capacity of the government to respond are crucial predictors of vulnerability, any of which could aggravate the threats to human health (Stanke et al., 2013; IPCC, 2014). Thus, drought impacts will affect different countries at varying degrees depending on the region, and the affected populations (being the poor and other vulnerable people those that tend to suffer higher negative repercussions (Sena et al., 2014)).

Particularly, geographical location is an important direct factor of vulnerability because people who lives in regions more affected by droughts or in regions that are prone to droughts or water shortages are highly vulnerable to the harmful health effects of droughts (Lohmann and Lechtenfeld, 2015). That is the case of arid or semiarid regions (e.g. Sena et al., 2014; Ebi and Bowen, 2016), where these effects could be exacerbated by a growth in population, as is expected in the case of Africa for the next 30 years (Kravitz, 2014). In addition, different magnitudes of drought impacts on health can occur between coastal and interior areas (e.g. Berman et al., 2017; Salvador et al., 2019), or between rural and urban locations (e.g. OBrien et al., 2014; Vins et al., 2015; Lohmann and Lechtenfeld, 2015; Berman et al., 2017). In particular, Berman et al. (2017) described that in the interior counties of Western USA where droughts occurred less frequently (e.g. eastern Great Plains), the risk for cardiovascular diseases and mortality in older adults was higher during worsening drought conditions in contrast to coastal areas (such as California, and the southwest), where exits a higher frequency of drought conditions. This fact occurs may be due to possible population acclimatization.

However, a comprehensive international review showed that more frequent and intense droughts might be sources of health vulnerability themselves for subsequent droughts, or when they are followed by other extreme events, such as floods (mainly by alterations in the degree of exposure or changes in sensibility and susceptibility of exposed people). The role of the floods after drought periods are particularly interesting because floods are associated to deaths, exacerbation of chronic diseases, increase of water- and vector-borne diseases, rise of respiratory infections as well as increase of malnutrition, mental health diseases or adverse birth outcomes (Alderman et al., 2012). Thus, the magnitude and

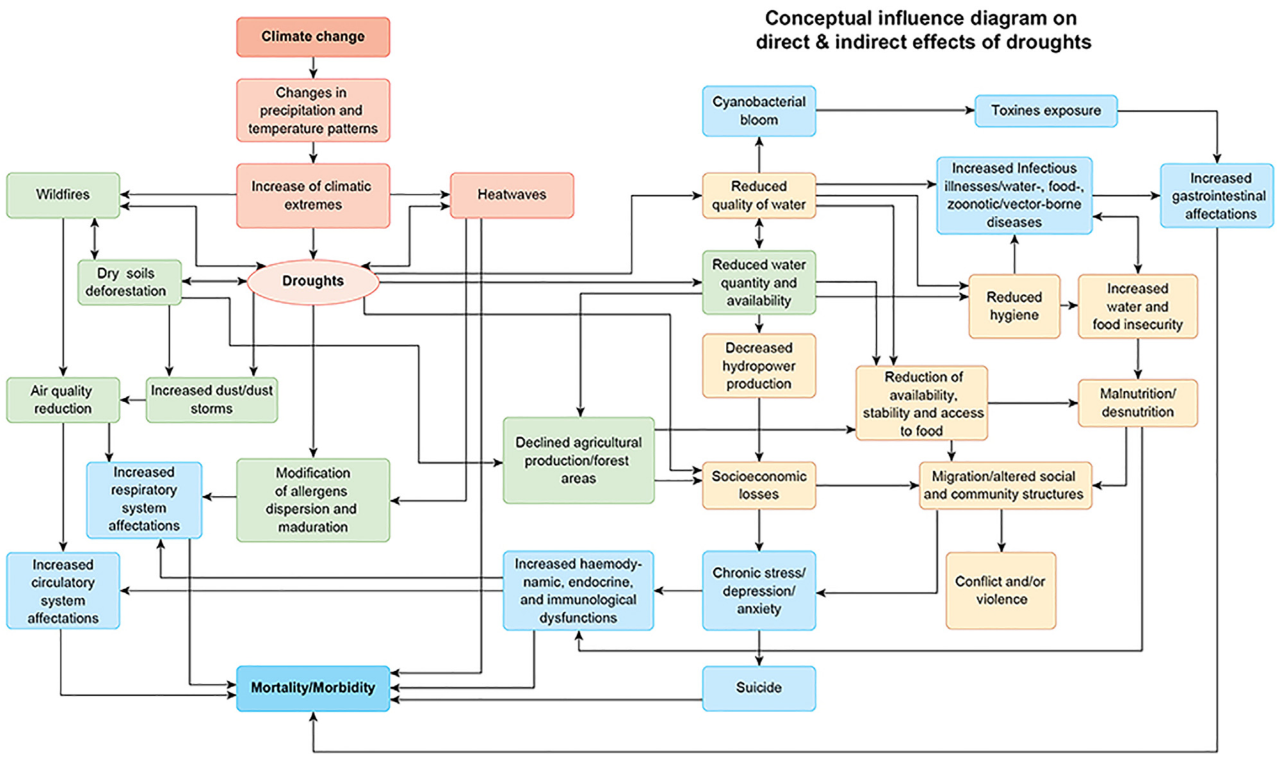

Fig. 1. Conceptual influence diagram on direct and indirect effects of droughts. The direct effects of droughts on environmental degradation and ecosystems modification were illustrated as well as the different processes and indirect pathways through which droughts impacts on society and human health in the context of climate change. Colour code: climatic, health, environmental and social aspects are represented in red, blue, green and yellow colours, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

health risk behaviour pattern could increase, especially if there is not adequate recover time of affected people between the different hydrological extreme events or if there is an inadequate adaptive capacity of the population (Ebi and Bowen, 2016).

Finally, it has been described that agricultural workers, smallholder producers, herders, and rural populations, whose economy and subsistence largely depend on agriculture, are the groups most vulnerable to drought hazards (Kallis, 2008; Edwards et al., 2014; Lohmann and Lechtenfeld, 2015). Destitute people, women (and particularly pregnant women), and groups that are physiologically more susceptible (e.g. children, older adults, and low socioeconomic status) have an increased vulnerability to the negative impacts of drought events (Kallis, 2008; Yusa et al., 2015). People with chronic conditions are also highly vulnerable to the negative health impacts associated with droughts because the occurrence of this hydrological extreme can exacerbate their conditions, making them less capable of facing other extreme climatic hazards (Yusa et al., 2015). In this aspect, regions such as West-, East-, and Southern Africa and Southern Asia are the most vulnerable regions to food insecurity (Krishnamurthy et al., 2014), where children are the most affected by malnutrition and mortality during droughts long term, which may have negative repercussions during their adult life (Lohmann and Lechtenfeld, 2015). On the other hand, reliable data from the World Health Organization (WHO) show heterogeneous differences between the different sexes related to the negative health impacts attributable to natural disasters (droughts, floods, and storms), with the highest levels of mortality generally being seen in women (IPCC, 2014). However, in rural populations of Australia (New South Wales) there was an increase in the incidence of suicide primarily in male farmers aged 30–49 associated with the incidence of drought events during 1970–2007 in contrast to the diminution the risk of suicide in females aged >30 years old during droughts (Hanigan et al., 2012).

4. Uncertainty

The study and characterization of droughts are very complex, and there are several uncertainties about the details of the relationship between the occurrence of these hydrological extremes and their effects on health, so more studies are necessary to understand the different mechanisms, in order to promote awareness of the risks and social and environmental vulnerabilities worldwide. The majority of studies have focused on the association between droughts and the effects on health through indirect mechanisms, and, although different hypotheses have been proposed, the biological mechanisms through which droughts affect health are not well understood (Berman et al., 2017). But, it is important to remark that there is a lack of systematic studies that tackle the following aspect that remains to be investigated: what measures and characteristics of droughts are the most predictive to reflect health effects (Balbus, 2017). To our knowledge, with the exception of Salvador et al. (2019), there are no studies that evaluate and compare the performance of different drought indicators (calculated as an index or indices) to quantifying the risks of this hydrological extreme on specific health effects particularly in consideration to the different forms of drought and periods of time in which these effects can be manifested. Thus, future studies that explore this relationship through the comparison of multiple drought exposure and models are needed.

In addition, a better understanding of the vulnerability associated with droughts as well as the mechanisms linked to this vulnerability is crucial, considering future negative climate change in order to reduced vulnerabilities. There are necessary more conclusive studies that evaluate different effects of drought (measured by different indices) in consideration to changing climate, conducting the control by sex and age groups of the population exposed in order to identify which index (or indices) are the best proxy for reflecting the health risks in different sectors of the population and determinate the most vulnerable groups. Furthermore, it is also essential to extend this type of analysis at large scales (eg. national level) toward obtaining broader conclusions than regional or local studies.

Therefore, it is necessary to implement global and regional strategies in prevention and adaptation plans to ensure mitigation of the different direct and indirect effects on environmental systems. In particular, human health should be considered, from the most immediate effects (e.g., water insecurity) to long-term effects (e.g., malnutrition), including the least visible (e.g., impairments in mental health), all with a focus on the most vulnerable groups in society.

This research initiative should be articulated via a set of primary objectives (as shown in Fig. 2):

- To exhaustive study the climatic conditions that affect different health parameters of the population in currently affected regions, with the objective of understanding patterns of behaviour. Health parameters should be related to the thresholds of environmental conditions (temperatures, precipitation, humidity, pollution) and the occurrence of droughts.
- To carry out systematic global and regional studies on health indicators attributable to different environmental conditions by quantifying Relative Risk (RR) and the percentage of Attributable Risk (AR) of different causes of daily morbidity and mortality linked with drought events measured by different indices using different statistical models). Variables should be mapped to assess geographical variations.
- To conduct an exhaustive systematic study that evaluates and quantifies the different repercussions (both direct and indirect impacts) monitoring drought conditions differentially by severity (mild, moderate, extreme and severe), intensity and frequency.
- To carry out methodological studies in which different types of indicators of droughts (and different accumulation periods) are evaluated, with the ultimate aim of identifying the optimal and most sensitive drought index (and time scale) to reflect and quantify the risks in terms of morbidity and mortality. In this way, it will be possible to establish a more precise classification of drought effects on health as short, medium or long term impacts.
- On the other hand, to obtain datasets of droughts at different temporal resolutions to conduct comparative studies on the quantification of health risks associated with droughts using daily, weekly, monthly and/or annual data series. This is important because in several regions of the word health data are not available in scales as precise as daily or weekly scales.
- To perform statistical models to control the effects of other extreme climatic phenomena associated with the occurrence of drought events, such as heatwaves, forest fires, and atmospheric pollution, as well as investigate the association between droughts and weather types. It is important to carry out a comparative study about the effects on health parameters only under drought periods and when this hydrological extreme occurs with other extreme climatic events in study regions. This fact allows evaluate direct and indirect impacts as well as analyse the synergic effects on health parameters.
- Other aspect that remain to be investigated is evaluate and compare changes in composition in particulate matter (eg. more toxicity) during droughts respect to no-droughts periods and analyse, in the case of this occur, if these lead to greater impacts. Although there are studies which reveal changes in particulate matter quantity associated to drought periods, as far as we know there is no evidence about changes in composition of toxic aerosols during drought conditions. In this context, Berman et al. (2017) discuss the possibility of changes in toxic-

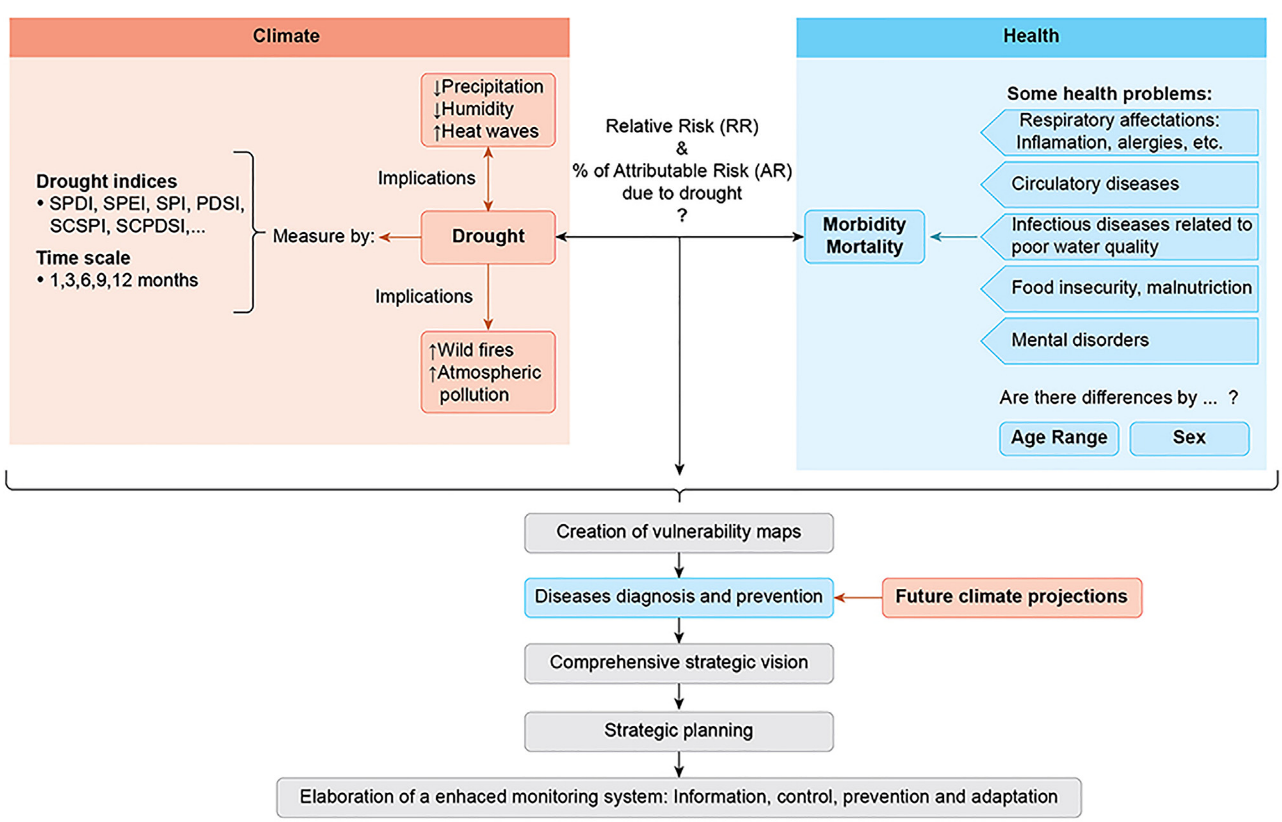

Fig. 2. Conceptual diagram of the methodological summary and protocol to follow for the here articulated research initiative for future years.

ity of PM2.5, however this fact was not tested.

- To carry out the quantification of different health risks (according to the diseases and causes of mortality described above) by age groups and gender for the population using statistical models, in order to identify the groups most vulnerable to the effects of droughts in terms of health. Also, to consider other vulnerability factors in statistical models and to compare the different health risks during different conditions (e.g. drought days and non-drought days in summer, spring, autumn, and winter months). For example, conduct comparative studies on the estimation of health risks associated to droughts in developed and developing countries under similar drought conditions to assess the role of socioeconomic factors and government measures as sources of vulnerability to drought impacts. On the other hand, to carry out differential analysis on drought effects taking into account seasonality will allow to know in a more precise way the different biological mechanism through which droughts specifically affect health.
- Estimating future scenarios and the probability of occurrence of the minimum, maximum, and mean climatic thresholds, as well as the incidence of extreme climatic events described in the previous points for different future climatic scenarios, making use of regional climate change projections (eg. RCP4.5 and RCP8.5 emissions scenarios). This will permit us to estimate the health risks associated with each of these future climatic conditions.
- To construct vulnerability maps for a better understanding of current and future risks associated with climate change, to improve monitoring, prevention, and adaptation systems.
- To investigate the potential of pre-operative seasonal and climatic as undertaken by the ECMWF (European Centre for Medium-Range Weather Forecasts) for the elaboration of an early warning system that could become operative and useful for the regional health services.
- To develop preventive and early-warning measures to achieve better adaptation plans that will allow for the mitigation of the possible harmful threats to human health in the near future, mainly focusing on the most vulnerable groups in order to reduce their vulnerability. Strengthen drought management measures of water and raise public awareness of possible future health risks of drought events.

Obtaining a complete understanding of the details on the link between the occurrence of different drought conditions and the different health effects is crucial to be able to take early measures of prevention and adaptation as well as reduce vulnerability in more susceptible groups, especially in consideration to future projections of climate change.

5. Conclusions

Droughts are complex socio-environmental hazards produced by mixtures of climatic, hydrological, environmental, socioeconomic, and cultural factors, and its study should be holistic by using different fields and institutions. Droughts are widely considered to be the costliest, most complex, most destructive, and the least understood phenomenon affecting more people than any other hazard. The definition and quantification of droughts are difficult and often uncertain. Droughts directly impact the environment and ecosystems through a reduction in both water availability and quality, reduced crops, and reduced forest yield back, as well as through an increase in the occurrence and intensity of fires. In addition, droughts may incorporate effects of other climatic extremes whose concurrent incidence may accelerate the development of droughts as well as increase the indirect risks on health. The majority of the effects on health are indirect and range from water-, food-, zoonotic-, and vector-borne diseases to malnutrition, socioeconomic impacts, migration, effects in mental health, morbidity, and mortality. The risks linked to droughts are heterogeneous and depend on the interaction between the regionś exposure to the events, and other vulnerability factors, such as previous vulnerability or the socioeconomic status of the population. In this discussion paper we want show that the study of effects of droughts on health is a topic of current concern, but there are some uncertainties about it, being necessary research that are focused on what characteristics of droughts as well as what measures (indexes of droughts and timescales) are the best proxy to identifying and estimating specific risk on human health systems. In addition, a better knowledge about the biological mechanisms through which drought conditions affect health as well as what mechanisms of vulnerability are involved are needed. More precise information will allow distinguish effects of droughts in short-, medium- and long- term impacts. Finally, a broader knowledge on this topic will be crucial to implement early prevention and adaptation measures, reduce vulnerabilities and to mitigate potential risks in future climate scenarios.

Declaration of Competing Interest

The authors declare no conflict of interest.

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Author contributions

Conceptualization, C.S.; Writing—Original Draft Preparation, C. S.; Writing—Review & Editing, C.S. R.N, L.G., C.L. and J.D.; Figures C.S.; Funding Acquisition, R.N and L.G.

References

Alderman, K., Turner, L.R., Tong, S., 2012. Foods and human health: a systematic review. Environ. Int. 47, 37–47.

Alpino, T.A., Martins de Sena, A.R., Machado de Freitas, C., 2016. Disasters related to droughts and public health-a review of the scientific literature. Ciênc. saúde coletiva 21 (3). https://doi.org/10.1590/1413-81232015213.21392015.

Bachmair, S., Stahl, K., Collins, K., Hannford, J., Acreman, M., Svoboda, M., Knutson, C., Helm Smith, K., Wall, N., Fuchs, B., Crossman, N.D., Overton Lan, C., 2016. Drought indicators revisited: the need for a wider consideration of environment and society. WIREs Water 3 (4), 516–536.

Balbus, J., 2017. Understanding droughtś impacts on human health. The Lancet Planetary Health. https://www.thelancet.com/journals/lanplh/article/PIIS2542-5196(17)30008-6/fulltext.

Bell, J.E., Brown, C.L., Conlon, K., Herring, S., Kunkel, K.E., Lawrimore, J., Luber, G., Schreck, C., Smith, A., Uejio, C., 2018. Changes in extreme events and the potential impacts on human health. Air Waste Manag. Assoc. 68 (4), 265–287. https://doi.org/10.1080/10962247.2017.1401017.

Berman, J.D., Ebisu, K., Peng, R.D., Dominici, F., Bell, M.L., 2017. Drought and the risk of hospital admissions and mortality in older adults in western USA from 2000 to 2013: a retrospective study. Lancet Planet Health 1 (1), e17–e25. https://doi.org/10.1016/S2542-5196 (17)30002-5.

Berry, H.L., Bowen, K., Kjellstrom, T., 2010. Climate change and mental health: a causal pathways framework. Int. J. Public Health 55 (2), 123–132.

Bifulco, M., Ranieri, R., 2017. Impact of drought on human health. Eur. J. Intern. Med. 46, e9–e10. https://doi.org/10.1016/j.ejim.2017.08.009.

Brown, L., Medlock, J., Murray, V., 2014. Impact of drought on vector-borne diseases-how does one manage the risk?. Public health I28, 29–37.

Brüntrup, M., Tsegai, D., 2017. Drought Adaptation and Resilience in Developing Countries. Deutsches Institut für Entwicklungspoliti (d.i.e) joint project with

United Nations. https://www.die-gdi.de/en/briefing-paper/article/drought-adaptation-and-resilience-in-developing-countries/.
Dai, A., 2011. Drought under global warming: a review. Wiley Interdiscipl. Rev. Clim. Change 2 (1), 45–65.
Ebi, K.L., Lobell, D., Field, C., 2010. Climate change impacts on food security and nutrition. SCNNews38: Climate Change: Food and Nutrition Security Implications. http://www.unscn.org/files/Publications/SCN_News/SCN_NEWS_38_03_06_10.pdf.
Ebi, K.L., Bowen, K., 2016. Extreme event as sources of health vulnerability: drought as an example. Weather Clim. Extremes 11, 95–102.
Edwards, B., Gray, M., Hunter, B., 2014. The impact of drought on mental health in rural and regional Australia. Soc. Indic. Res. https://doi.org/10.1007/s11205-014-0638-2.
European commission, 2010. Water Scarcity and Drought in the European Union.
Franchini, M., Mannucci, P.M., 2015. Impact on human health of climate changes. Eur. J. Int. Med. 26 (1), 1–5.
García-Herrera, R., Díaz, J., Trigo, R.M., Luterbacher, J., Fischer, E.M., 2010. A review of the European summer Heat Wave of 2003. Crit. Rev. Environ. Sci. Technol. 40, 267–306. https://doi.org/10.1080/10643380802238137.
Gebremeskel, G.H., Tang, Q., Sun, S., Huang, Z., Zhang, X., Liu, X., 2019. Droughts in East Africa: causes, impacts and resilience. Earth Sci. Rev. https://doi.org/10.1016/j.earscirev.2019.04.015.
Gupta, J., Hurley, F., Grobicki, A., Keating, T., Stoett, P., Baker, E., Guhl, A., Davies, J., Ekins, P., 2019. Communicating the health of the planet and its links to human health. Lancet Planetary Health 3 (5), e204–e206. https://doi.org/10.1016/S2542-5196(19)30040-3.
Hanigan, I.C., Butler, C.D., Kokic, P.N., Hutchinson, M.F., 2012. Suicide and drought in New South Wales, Australia, 1970–2007. Proc. Natl. Acad. Sci. USA 109, 13950–13955.
Hayes, M., 2002. Public health impacts of drought. In: Proceedings of the American Meteorological Society's 15th Conference on Biometeorology and Aerobiology, pp. 223–225.
He, B., Ciu, X., Wang, H., Chen, A., 2014. Drought: the most important physical stress of terrestrial ecosystems. Acta Ecol. Sin. 34, 179–183.
Hu, Y., Wang, S., Yang, X., Kang, Y., Ning, G., Du, H., 2019. Impact of winter droughts on air pollution over Southwest China. STOTEN 664, 724–736.
IPCC, 2014. Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Field, C. B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P .R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, p. 1132.
Kallis, G., 2008. Droughts. Annu. Rev. Environ. Resour. 33, 85–118.
Keim, M.E., 2015. Chapter 2. EXTREME WEATHER EVENTS The role of public health in disaster risk reduction as a means for climate change adaptation. In Global climate change and human health: From science to practice, eds. G. Luber and J. Levine, p. 43.
Keyantash, J., Dracup, J.A., 2002. The quantification of drought: an evaluation of drought indices. BAMS. https://doi.org/10.1175/1520-0477-83.8.1167.
Kravitz, J.D., 2014. Drought: a global environmental concern. The Lancet Planetary Health 1 (4), PE130-E131.
Krishnamurthy, K., Lewis, K., Choularton, R.J., 2014. Climate Impacts on food security and nutrition: A review of existing knowledge. World Food Programe https://documents.wfp.org/stellent/groups/public/documents/communications/wfp258981.pdf?_ga=2.91201052.78389462.1557747291-1116074375.1557747291.
Lehman, P.W., Kurobe, T., Lesmeister, S., Baxa, D., Tung, A., Teh, S.J., 2016. Impacts of the 2014 severe drought on the Microcystis bloom in San Francisco Estuary. Harmful Algae 63, 94–108.
Lohmann, S., Lechtenfeld, T., 2015. The effect of Drought on Health outcomes and health expenditures in rural Vietnam. World Dev. 72, 432–448. https://doi.org/10.1016/j.worlddev.2015.03.003.
López-Vélez, R., Molina Moreno, R., 2005. Cambio climático en España y riesgo de enfermedades infecciosas y parasitarias transmitidas por artrópodos y roedores. Rev. esp salud pública 79, 177–190.
Ma, M., Ren, L., Yuan, F., Jiang, S., Liu, Y., Kong, H., Gong, L., 2013. A new standardized Palmer drought index of hydro-meteorological use. Hydrol. Process. 28 (23) https://onlinelibrary.wiley.com/doi/abs/10.1002/hyp.10063.
McCann, G.C.D., Moore, A., Walker, M.E., 2011. The water/health nexus in disaster medicine: I. Drought versus flood. Curr. Opin. Environ. Sustain. 3, 480–485.
MINECO, 2019. https://www.miteco.gob.es/es/agua/temas/observatorio-nacional-de-la-sequia/que-es-la-sequia/Observatorio_Nacional_Sequia_1_1_tipos_sequia.aspx.
Mishra, A.K., Singh, V.P., 2010. A review of drought concepts. J. Hydrol. 391, 202–216.
Monteiro, J., João Silva, A., Mortal, A., Aníbal, J., Moreira da Silva, M., Oliveira, M., Sousa, N., 2019. Increase 2019. Proceedings of the 2nd International Congress on Engineering and Sustainability in the XXI Century.
Obasi, O.P., 1994. WHÓs role in the international decade for natural disaster reduction. Bull. Am. Meteorol. Soc. 75, 1655–1661.
OBrien, L.V., Berry, H.L., Coleman, C., Hanigan, I.C., 2014. Drought as a mental health exposure. Environ. Res. 131, 181–187.
Palmer, W.C., 1965. Meteorological drought. US Weather Bureau Research Paper, 45.
Quiring, S., 2015. Hydrological, floods and droughts|drouhgt. Encyclopedia Atmos. Sci. 193–200. https://doi.org/10.1016/B978-0-12-382225-3.00037-2.
Salvador, C., Nieto, R., Linares, C., Diaz, J., Gimeno, L., 2019. Effects on daily mortality of droughts in Galicia (NW Spain) from 1983 to 2013. STOTEN 662, 121–133.
Sartore, G.M., Kelli, B., Stain, H.J., 2007. Drought and its effect on mental health—how GPs can help. Aust Fam Physician 36 (12), 990–993.
Selby, J., Dahi, O.S., Fröhlich, Hulme, M., 2017. Climate change and the Syrial civil war revisited. Political Geogr. 60, 232–244.
Sena, A., Barcellos, C., Freitas, C., Corvalan, C., 2014. Mananging the health impacts of drought in Brazil. Int. J. Environ. Res. Public Health 11 (10), 10737–10751.
Shukla, J., 2013. Extreme Weather Events and Mental Health: Tackling the Psychological Challenge. ISRN Public Health, vol. 2013, Article ID 127365. Hindawi Publishing Corporation, p. 7. https://doi.org/10.1155/2013/127365.
Smith, L.T., Aragão, L.E.O.C., Sabel, C.E., Nakaya, T., 2014. Drought impacts on children's health in the Brazilian Amazon. Sci. Rep. 4, 3726.
Spinoni, J., Vogt, J., Naumann, G., Barbosa, P., 2018. Will drought events more frequent and severe in Europe?. Int. J. Climatol. 38 (4), 1718–1736.
Spinoni, J., Barbosa, P., De Jager, A., McCormick, N., Naumann, G., Vogt, J.V., Magni, D., Masante, D., 2019. A new global database of meteorological drought events from 1951 to 2016. J. Hydrol.: Reg. Stud. 22. https://doi.org/10.1016/j.ejrh.2019.100593.
Stanke, C., Kerac, M., Prudhomme, C., Medlock, J., Murray, V., 2013. Health effects of drought: a systematic review of the evidence. PLoS Curr. https://doi.org/10.1371/cualporrents.dis.7a2cee9e980f91ad7697b570bcc4b004 (pii:ecurrents.dis.7a2cee9e980f91ad7697b570bcc4b004).
Tirado-Blazquez, M.C., 2010. Cambio climático y salud. Informe SESPAS 2010. Gac. Sanit. 24, 78–84.
Valiente, M.O., 2001. Sequía: definiciones, tipologías y métodos de cuantificación. Investigaciones geográficas 26, 59–80.
Vicente Serrano, 2006. Differences in Spatial Patterns of drought on different time scales: an analysis of the Iberian Peninsula. Water Resour. Manage. 20, 37–60. https://doi.org/10.1007/s11269-006-2974-8.
Vicente-Serrano, S.M., López-Moreno, J., Drumond, A., Gimeno, L., Nieto, R., Morán-Tejeda, E., Lorenzo, Lacruz, J., Beguería, S., Zabalza, J., 2011. Effects of warming processes on droughts and water resources in the NW Iberian Peninsula (1939–2006). Clim Res. 48, 203–212.
Vicente-Serrano, S.M., Beguería, S., Lorenzo-Lacruz, J., Camarero, J.J., López-Moreno, J.I., Azorin-Molina, C., Revuelto, J., Morán-Tejeda, E., Sánchez-Lorenzo, A., 2012. Performance of drought Indices for Ecological, Agricultural, and Hydrological Applications. Earth Interact. 16, 1–27.
Vicente-Serrano, S.M., Lopez-Moreno, J.-I., Beguería, S., Lorenzo-Lacruz, J., Sanchez-Lorenzo, A., García-Ruiz, J.M., Azorin-Molina, C., Morán-Tejeda, E., Revuelto, J., Trigo, R., Coelho, F., Espejo, F., 2014. Evidence of increasing drought severity caused by temperature rise in southern Europe. Environ. Res. Lett. 9 (4), 044001. https://doi.org/10.1088/1748-9326/9/4/044001.
Vicente-Serrano, S.M., 2016. Foreword: drought complexity and assessment under climate change conditions. Cuadernos de investigación geográfica 42 (1). https://doi.org/10.18172/cig.2961.
Vicente-Serrano, S.M., Tomas-Burguera, M., Begueria, S., Reig, F., Latorre, B., Peña-Gallardo, M., Yolanda Luna, M., Morata, A., González-Hidalgo, J.C., 2017. A high resolution dataset of drought indices for Spain. Data 2 (3), 22.
Vins, H., Bell, J., Saha, S., Hess, J.J., 2015. The mental health outcomes of drought: a systematic review and causal process diagram. Int. J. Environ. Res. Public Health 12 (10), 13251–13275.
Walter, J.M., Lopes, F.A.C., Lopes-Ferreira, M., Vidal, L.M., Leomil, L., Melo, F., De Axevedo, G., Oliveira, R.M.S., Medeiros, A.J., Melo, A.S.O., De Rezende, C.E., Tanuri, A., Thompson, F.L., 2018. Occurrence of Harmful Cyanobacteria in Drinking water from a severely Drought-impacted Semi-arid Region. Front. Microbiol. 9, 176. https://doi.org/10.3389/fmicb.2018.00176.
Wang, Y., Xie, Y., Dong, W., Ming, Yi, Wang, J., Shen, Lu., 2017. Adverse effects of increasing drought on air quality via natural processes. Atmos. Chem. Phys. 17, 12827–12843. https://doi.org/10.5194/acp-17-12827-2017.
Watts, N. et al., 2015. Health and climate change: policy responses to protect public health. Lancet 386 (10006), 1861–1914.
Watts, N. et al., 2017. The lancet countdown: tracking progress on health and climate change. Lancet 389 (100074), 1151–1164.
Wells, N., Goddard, S., Hayes, M.J., 2004. A Self-Calibrating Palmer Drought Severity Index. Journal of Climate 17 (12), 2335–2351. https://doi.org/10.1175/1520-0442(2004)017<2335:ASPDSI>2.0.CO;2.
WHO, 2018. Climate change and health. World Health Organization. Available online: https://www.who.int/news-room/fact-sheets/detail/climate-change-and-health (accessed on 20/03/2019).
Wilhite, D.A., 2000. Drought as a Natural Hazard: Concepts and Definitions. DigitalCommons@University of Nebraska-Lincoln. Chapter 1, pp. 1–18.
Wilhite, D.A., Svoboda, M.D., Hayes, M.J., 2007. Understanding the complex impacts of drought: a key to enhancing drought mitigation and preparedness. Water Resour. Manage. 21 (5), 763–774.
World Meteorological Organization (WMO) and Global Partnership (GWP), 2016. Handbook of Drought Indicators and Indices (M.Svoboda and B.A. Fuchs). Integrated Drought Management Programme (IDMP), Integrated Drought Management Programme (IDMP), Integrated Drought Management Tools and Guidelines Series 2. Geneva. ISBN 978-92-63-11173-9.
Yu, H., Zhang, Q., YuXu, C., Du, J., Sun, P., Hu, P., 2019. Modified palmer drought severity index: model improvement and application. Environ. Int. 10,. https://doi.org/10.1016/j.envint.2019.104951 104951.
Yusa, A., Berry, P., Cheng, J.J., Ogden, N., Bonsal, B., Stewart, R., Waldick, R., 2015. Climate change, drought and human health in Canada. Int. J. Environ. Res. Public Health 12 (7), 8359–8412.