A review of drought indices: predominance of drivers over impacts and the importance of local context

Sarra Kchouk¹, Lieke A. Melsen², David W. Walker¹, Pieter R. van Oel¹

¹Water Resources Management Group, Wageningen University, Wageningen, 6708PB, The Netherlands
²Hydrology and Quantitative Water Management Group, Wageningen University, Wageningen, 6708PB, The Netherlands

Correspondence to: Sarra Kchouk (sarra.kchouk@wur.nl)

Abstract. Drought monitoring and Early Warning Systems (DEWS) are seen as helpful tools to tackle drought at an early stage and reduce the possibility of harm or loss. They usually include indices attributed to meteorological, agricultural and/or hydrological drought: physically based drought drivers. These indices are used to determine the onset, end and severity of a drought event. Drought impacts are less monitored or even not included in DEWS. Therefore, the likelihood of experiencing drought impacts is often simply linearly linked to drivers of drought. The aim of this study is to evaluate the validity of the assumed direct linkage between drivers of drought and drought impact. We reviewed scientific literature on both drivers and impacts of drought. We conducted a bibliometric analysis based on 5000+ scientific studies in which selected drought indices (drivers) and drought impacts were mentioned in relation to a geographic area. Our review shows that there is a tendency in scientific literature to focus on drivers of drought, with the preferred use of meteorological and remotely sensed drought indices. Studies reporting drought impacts are more localised, with relatively many studies focusing on Sub-Saharan Africa and Australasia for impacts with regard to food security and water security, respectively. Our review further suggests that drought-impact studies are dependent on both the physical and human processes occurring in the geographic area, i.e. the local context. With the aim of increasing the relevance and utility of the information provided by DEWS, we argue in favour of additional consideration of drought impact indices oriented towards sustainable development and human welfare.

1 Introduction

Drought is a threat to a wide range of human activities in virtually all climate zones and countries (Van Loon et al., 2016; Bachmair et al., 2016; Van Lanen et al., 2017). It is an elusive phenomenon without a clear onset and demise. In contrast to other hazards such as floods, landslides or earthquakes, drought has a creeping nature causing impacts to persist for many years (Kim et al., 2019). Consequently, impacts can be cumulative for consecutive periods of droughts, devastating both ecosystems and societies (Bachmair et al., 2016; Van Lanen et al., 2017).

Many concepts exist for defining a drought (Santos Pereira et al., 2009; Lloyd-Hughes, 2014). Definitions of drought are either conceptual or operational. Conceptual definitions of drought are descriptive and highlight the natural hazard element: for example, precipitation below what is expected or normal (Knutson et al., 1998). Operational definitions of drought highlight...
practical implications in an attempt to identify the onset, severity, and cessation of drought periods (Mishra and Singh, 2010). For example, the UN Convention to Combat Drought and Desertification (UN Secretariat General, 1994) defines drought as “when precipitation has been significantly below normal recorded levels, causing serious hydrological imbalances that adversely affect land resource production systems”.

The numerical value of hydro-climatic variables is associated to three main types of drought: meteorological, agricultural (or soil moisture) and hydrological droughts. These variables are in fact drivers, which refer to the contributing or counteracting factors that affect the development of droughts (Seneviratne, 2012). Those drivers are used by many drought studies as the framework to represent drought propagation. The temporal propagation of drought is often considered to be a sequence occurring in an almost linear order (Wilhite and Glantz, 1985; Zargar et al., 2011; Bachmair et al., 2016), and in which humans have no direct influence. This is a simplification of a complex process, where it is considered that an anomaly (e.g. lower precipitation, higher temperature than average) or a standardised normalisation of the values of those drivers will lead to a cascade reaction influencing the magnitude of other physical variables and leading in turn to the subsequent type of drought. As such, hydrological drought results from persistence in duration of agricultural (soil moisture) drought, which itself is due to persistence of meteorological drought.

Drought monitoring and Early Warning Systems (DEWS) aim to monitor the drivers of drought to predict drought. They aim to tackle drought at an early stage to reduce the possibility of harm or loss. For assessing the severity of a drought, physical variables are usually translated into indices of drought. The difference between their values and the threshold used to define the level of dryness is considered to depict the severity of a drought (Vogt et al., 2018). Drought impacts, such as water- and food security, are rarely continuously monitored or even included in DEWS. This is understandable as there is already a plethora of definitions for drought and drought types, and there are at least as many possibilities for defining impacts (Mishra and Singh, 2010; Wilhite, 2000; Santos Pereira et al., 2009). Drought impacts are non-structural, difficult to quantify or monetise, and can be direct or indirect due to the extended nature, in time and area, of drought (Wilhite et al., 2007; Logar and Van den Bergh, 2011; Bachmair et al., 2016). But in the current configuration of DEWS, the presumed likelihood of experiencing impacts is mainly linked to the severity of climatic features only (e.g. ;US National Drought Mitigation Center; Princeton Flood and Drought Monitors; Brazilian Drought Monitor).

The aim of this study is to review scientific reporting on drought drivers and drought impacts for affected regions and analyse how these two compare. This research aims to improve understanding on the linkage and separation between drought drivers and drought impacts, and to provide directions to further improve the accuracy of the information provided by DEWS. We retrieved scientific studies from categorised geographic areas in which selected drivers of drought and impacts of drought are mentioned. The components of drought drivers and impacts on which the literature focused were explored and compared for different areas of the world.
2 Data and Methods

2.1 Methodological approach

The methodological approach comprises three steps:

Step 1. Exploring which drought drivers are the most recurrent in the scientific literature. We investigated which indices of drought drivers are most frequently used in scientific drought-related studies and to what drought type they were linked. For each of these scientific studies we also retrieved the country of focus. This allowed us to identify: the most frequently mentioned type of drought for different geographic regions, and the prevalent drought indices used in scientific studies.

Step 2. Exploring which drought impacts are the most recurrent in the scientific literature. In contrast with drought drivers, for drought impacts there are no established indices commonly used in DEWS and in scientific studies. We thus retrieved from scientific articles, keywords associated to drought impacts related to water security and food security. This allowed the identification of the most frequently mentioned water- and food-related drought impacts.

Step 3. Comparing the findings of Steps 1 and 2. This enabled evaluation of the alignment between reported drought types and impacts, with regard to the number of publications and differences in geographic focus.

2.2 Data

We considered the number of studies about drought indices and drought impacts, respectively, and their geographical distribution as our metrics. We selected commonly used indices to depict operational types of droughts (Svoboda and Fuchs, 2016) and the indices commonly used by water managers (Bachmair et al. (2016). This resulted in 32 indices that we linked to three main drought types (Table 1): meteorological (9 indices), soil moisture/agricultural (15) and hydrological (8) drought.

| Meteorological Drought indices studies | Total number of studies of drought indices : 5567 | Total number of studies mentioning a country: 4023 | Studies not mentioning a country : 27.7% | Top 3 subject area |
|--------------------------------------|-----------------------------------------------|-------------------------------------------------|----------------------------------------|--------------------|
| “Meteorological drought” Indices mentioned in the study | Acronym | Input data | Number of studies | Studies mentioning a country | Portion of studies not mentioning a country (%) |
| Standardized Precipitation Index | SPI | Precipitation | 2451 | 1812 | 26.1 | 1) Environmental Science 2) Earth and Planetary Sciences 3) Agricultural and Biological Sciences |
| Standardized Precipitation | SPEI | Precipitation, temperature | 1059 | 751 | 29 | 1) Environmental Science 2) Earth and Planetary Sciences |
| Index                                      | Subject Area                                      | Precipitation, temperature | 2021 | 2022 | Studies not mentioning a country (%) | Top 3 subject area |
|--------------------------------------------|--------------------------------------------------|------------------------------|-------|------|--------------------------------------|--------------------|
| **Evapotranspiration Index**               | 3) Agricultural and Biological Sciences           |                              |       |      |                                      |                    |
| **Aridity Index**                          | 1) Environmental Science  2) Earth and Planetary Sciences  3) Agricultural and Biological Sciences | AI                            | 247   | 182  | 26.3                                 |                    |
| **Precipitation Deciles**                  | 1) Earth and Planetary Sciences  2) Environmental Science  3) Engineering | Deciles                      | 12    | 9    | 25                                   |                    |
| **Keetch-Byram Drought Index**             | 1) Environmental Science  2) Agricultural and Biological Sciences  3) Earth and Planetary Sciences | KBDI                          | 84    | 66   | 21.4                                 |                    |
| **Palmer Drought Severity Index**          | 1) Environmental Science  2) Earth and Planetary Sciences  3) Agricultural and Biological Sciences | PDSI                          | 1279  | 867  | 32.2                                 |                    |
| **Percent of Normal Precipitation (Index)**| 1) Environmental Science  2) Earth and Planetary Sciences  3) Agricultural and Biological Sciences | PNPI                          | 23    | 18   | 21.7                                 |                    |
| **Rainfall Anomaly Index**                 | 1) Earth and Planetary Sciences  2) Environmental Science  3) Agricultural and Biological Sciences | RAI                           | 304   | 244  | 19.7                                 |                    |
| **Self-Calibrated Palmer Drought Severity Index** | 1) Earth and Planetary Sciences  2) Environmental Science  3) Agricultural and Biological Sciences | scPDSI                        | 108   | 74   | 31.5                                 |                    |
| **Agricultural and Soil Moisture Drought indices studies** | 1) Earth and Planetary Sciences  2) Environmental Science  3) Agricultural and Biological Sciences |                              | Total number of studies of drought indices : 5085 | Total number of studies mentioning a country : 3137 | Studies not mentioning a country : 38.3% | Top 3 subject area |
| **“Agricultural drought” mentioned in the study** | 1) Earth and Planetary Sciences  2) Environmental Science  3) Agricultural and Biological Sciences | CMI                           | 43   | 20   | 53.5                                 |                    |

https://doi.org/10.5194/nhess-2021-152
Preprint. Discussion started: 17 June 2021
© Author(s) 2021. CC BY 4.0 License.
| Index Description | Index acronym | Notes | SCI | SCI-1/2 | SCI-1/3 | SCI-2/3 |
|------------------|--------------|-------|-----|---------|---------|---------|
| Evaporative Stress Index | ESI | Remotely sensed potential evapotranspiration | 88 | 42 | 53.3 |
| Evapotranspiration Deficit Index | ETDI | Soil water in the root zone on a weekly basis, which is computed from SWAT model | 17 | 13 | 23.5 |
| Enhanced Vegetation Index | EVI | NIR/red/blue surface reflectances, canopy background adjustment, coefficients of the aerosol resistance for correction for aerosol influences in the red band. | 305 | 206 | 32.2 |
| Normalized Difference Vegetation Index | NDVI | Spectral reflectance measurements acquired in the red and near-infrared regions | 2041 | 1288 | 36.9 |
| Leaf Area Index | LAI | Leaf and ground area | 1152 | 583 | 49.4 |
| Palmer Moisture Anomaly Index – known as the Palmer Z index | PZI | Derivative of the PDSI calculation precipitation, temperature, available water content | 47 | 30 | 36.2 |
| Soil Adjusted Vegetation Index | SAVI | Spectral reflectance measurements acquired in the red and near-infrared regions, with the addition of a soil brightness correction factor | 68 | 37 | 45.6 |
| Soil Moisture Anomaly | SMA | Precipitation, temperature, available water content | 138 | 87 | 37.0 |
| **Soil Moisture Deficit Index** | SMDI | soil water in the root zone on a weekly basis, which is computed from SWAT model | 13 | 10 | 23.1 | 1) Environmental Science  
2) Earth and Planetary Sciences  
3) Agricultural and Biological Sciences |
|-------------------------------|------|---------------------------------------------------------------------------------|----|----|-------|----------------------------------------------------------------------------------|
| **Soil Water Deficit Index** | SWDI |                                                                                  | 33 | 26 | 21.2 | 1) Earth and Planetary Sciences  
2) Agricultural and Biological Sciences  
3) Environmental Science |
| **Soil Water Storage**        | SWS  | available water content, reservoir, soil type, soil water deficit                | 717 | 494 | 31.1 | 1) Agricultural and Biological Sciences  
2) Environmental Science  
3) Earth and Planetary Sciences |
| **Vegetation Condition Index**| VCI  | (same as) NDVI                                                                  | 271 | 187 | 30.1 | 1) Earth and Planetary Sciences  
2) Agricultural and Biological Sciences  
3) Environmental Science |
| **Vegetation Drought Response Index** | VegDRI | SPI, PDSI, percentage annual seasonal greenness, start of season anomaly, land cover, soil available water capacity, irrigated agriculture and defined ecological regions | 14 | 13 | 7.1 | 1) Earth and Planetary Sciences  
2) Agricultural and Biological Sciences  
3) Environmental Science |
| **Vegetation Health Index**   | VHI  | NDVI and brightness temperature, both from thermal bands                         | 138 | 101 | 26.8 | 1) Earth and Planetary Sciences  
2) Agricultural and Biological Sciences  
3) Environmental Science |
| **Hydrological Drought indices studies** | | **Total number of studies of drought indices : 550** | **Total number of studies mentioning a country : 344** | **Studies not mentioning a country : 37.5%** | **Top 3 subject area** |
| **“Hydrological drought” Indices mentioned in the study** | | **Input data** | **Number of studies** | **Studies mentioning a country** | **Portion of studies not mentioning a country (%)** |
| **Reservoir Level**           | | Water levels in reservoirs                                                       | 72 | 35 | 51.4 | 1) Environmental Science  
2) Engineering  
3) Earth and Planetary Sciences |
| **Palmer Hydrological Drought Index (PHDI)** | | precipitation, temperature, available water content                             | 58 | 34 | 41.4 | 1) Environmental Science  
2) Earth and Planetary Sciences  
3) Agricultural and Biological Sciences |
We opted for Scopus to retrieve the scientific publications of interest as it is the database covering the largest range of both, peer-reviewed literature type (scientific journals, books and conference proceedings), and disciplinary fields (science,
We then searched in the Scopus database for queries strictly including “drought” AND “[the indicator]” in the title, abstract and authors’ keywords of the studies. We repeated the queries for each indicator individually as we were interested in knowing country-based preferences. The sum of the individual indices linked to drought queries returned 4137 articles for the “meteorological” drought type of indices, 2799 articles linked to “agricultural” drought and 393 articles linked to “hydrological” drought. The title, authors, author’s keywords, year of publication, journal name and abstract were retrieved using the Bibliometrix package (Aria and Cuccurullo, 2017) executed on R (version 4.0.0) following Addor and Melsen (2019). In the title, keywords and abstract of each paper, names of countries were identified, corresponding to the area of application of the study. The same approach was followed for the drought impacts. We grouped drought impacts into two focus categories: food security and water security. Their keywords are indicated in Table 1. The queries included “drought” AND selected “[drought impact]”. This resulted in 4764 articles linking drought to food security and 805 articles linking drought to water security.

All articles were published between 1960 and March 2021 and the exact queries for both drought indices and impacts are included in Table A1. Even though we recognise drought can impact ecosystems, this topic was excluded from the analysis for reasons of brevity. The dataset and the script used for its analysis are both available for consultation (Kchouk et al., 2021).

Many scientific studies are methodological; their goal can be the validation, calibration or improvement of the indices, thus, not all studies have a focus country. We only considered studies mentioning a country in their title, abstract and keywords; this being the only criteria of inclusion or rejection of papers in our analysis. This reduced the number of studies including a name of a country in their title, abstract and keywords by 28% for drought indices and by 44% for drought impacts. We also did a manual verification on some of the scientific studies to see if the association with a country was valid. This allowed us to bring some corrections to the metadata to avoid incorrect associations (e.g. removing mentions of the “Indian Ocean” that led to the incorrect association of the studies to India; removing the copyrights, generally in the end of the abstract, referring to another country than the one of the study).

### 3 Results

#### 3.1 Drought types and indices

The indices mentioned in the drought-related studies were classified according to the categories used in Table 1; their frequency of occurrence is shown in Fig. 1. Meteorological drought (MD) indices are reported most frequently, followed by agricultural or soil moisture drought indices (AD), and hydrological drought indices (HD). The most frequently mentioned indicator is the Standardised Precipitation Index (SPI), followed by the Normalised Difference Vegetation Index (NDVI). HD indices are less frequently utilised in comparison to the two other categories.
Figure 01: Treemap showing the proportion of indices for different drought types (blue is meteorological, green is agricultural and soil moisture drought, and orange is hydrological drought) employed in the title, abstract and keywords of drought-related studies on Scopus. The number indicates the number of studies including a country in their title, abstract or authors’ keywords.

For the regions of Australia-Oceania, Middle-East and North Africa (MENA) and Sub-Saharan Africa (SSA), there are fewer studies utilising HD indices than for the other regions (Fig. 2). Further geographical differences are observed from Fig. 2. Most areas resemble the overall pattern shown in Fig. 1; exceptions are Australia-Oceania and Sub-Saharan Africa, where AD indices are most frequently reported.
Figure 02: Barplot showing the proportion of drought type studies per region of the world, according to the drought indices referred to in the title, abstract and keywords of drought-related studies on Scopus.

In addition, not only are MD indices the most investigated, they are also the most associated with a country in studies, in comparison to AD, HD and impacts (Table 1). MD indices represents 53 % of the scientific studies while AD represents 42 % and HD, only 5 %. This indicates that in most of the studies, rainfall and the temperature are the dominant criteria utilised to report the occurrence of drought. Such a result is expected because of the ease of use of MD indices. We further develop this point in Sect. 4.3.

3.2 Drought-related impacts: food security and water security

Globally, there were five times more studies linking drought to food-security than drought to water-security (Fig. 3). This pattern is the same for most areas of the world. For Sub-Saharan Africa the predominance of food security indices is most pronounced (93%), followed by Asia and Europe (84%). Australia-Oceania is the only region where drought-related water security studies predominate over food security studies (52%), while Sub-Saharan Africa is the region where it is reported the least (6.6%).
Figure 03: Barplot showing the proportion of food and water security studies related to drought per region of the world on Scopus.

3.3 Geographic patterns for indices of drivers and impacts

Figure 4 shows that drought-drivers studies are quite evenly distributed across the regions except for SSA. The height of the dark blue boxes is substantially smaller than the others, suggesting that the share of SSA in drought-drivers studies is minor.
In the same way, two geographical patterns appear in the share of drought-related impacts studies. The height of the boxes of SSA and Australia-Oceania for food and water securities, respectively, related to drought is significantly superior to those of the other regions for the same indicator category. This means that food security related to drought is most frequently reported for SSA and that water security related to drought is most frequently reported for Australia-Oceania. Similarly, drought-related water security is least reported for Europe.

The geographical pattern of drought drivers and impact studies seen in Fig.4 is also present in the cartogram representations in Fig. 5. First, the three drought drivers categories appear to have the same pattern of investigation, all mostly focused on northern high-income countries. The United States and Mexico, North-Mediterranean countries and Australia-Oceania are strongly focusing on drivers in drought-related studies. Middle-income countries with high demographic and economic growth such as China, India and Iran also see a focus on drought-related drivers. They stand out from their geographic neighbours that are almost disappearing from the map.
In contrast, the African continent is strongly under-represented in terms of drought drivers studies, particularly with regard to meteorological and hydrological drought indices, with notable exceptions for Ethiopia, Kenya and South Africa. However, the...
distribution of agricultural and soil moisture drought studies appears to be more even in African countries, and higher in Sahelian countries.

Looking at the geographical repartition of drought-related impacts studies (Fig. 5d and 5e), two main observations are notable. First, the repartition of the impacts studies differs from the drivers studies. Second, both impacts, food and water security, show a different geographic pattern. Water security related to drought is most frequently investigated for Australia, the USA and Mexico, Brazil, the Middle East and South Africa. In contrast, food security is most commonly investigated for India, Ethiopia, Kenya and other African countries.

4 Discussion

This bibliometric study shows that unbalanced attention is given to drought drivers and impacts across the world. In this discussion section, we start by raising four hypotheses to explain why some features of drought are more frequently reported for some regions or countries than for others. The four hypotheses relate to: physical conditions (Sect. 4.1), socio-economic conditions (Sect. 4.2), data availability (Sect. 4.3), and scientific interests and orientation (Sect. 4.4). We continue by discussing potential limitations in our methodological approach (Sect. 4.5). We posit that these four hypotheses are also the four dimensions that are inherent to the local context of a geographic area. Drought monitoring is influenced by these to accurately predict droughts, their severity and impacts. In that sense, we end by formulating recommendations (Sect. 4.6) about shifting the scope of drought metrics to match the local context of a specific drought events.

4.1 Physical conditions

The most notable result from Sect. 3 is the more abundant investigation of MD over AD and HD (except in SSA and Australia-Oceania), with the SPI being the most used indicator in drought-related studies.

By focusing on MD, it is mainly the deficit of precipitation that is investigated. In humid areas, tropical, continental or temperate climates, a deficit of precipitation is less likely to affect the overall physical water scarcity and cause water shortage. In that sense, the occurrence of a drought is only statistically-based and not reflecting a true water deficit for the demand, only a below average situation (which is, however, in line with formal definitions of drought). In arid and semi-arid climates with lower levels of precipitation, it is recommended to use SPI cautiously because it can fail to indicate drought occurrence (Wu et al., 2007) and opt instead for indices that include evapotranspiration like the SPEI (Salimi et al., 2021). In such areas where evapotranspiration plays a larger role with regard to evaporative demand, water shortage is more common. For arid and semi-arid areas with low average rainfall and a higher risk of water scarcity, it may be more appropriate to determine water deficit at the crop, field or farm scale. This could explain the more frequent use of AD indices in the more arid Australian-Oceanian and Sub-Saharan regions (Fig. 2 & 4) that mainly monitor vegetation (NDVI, LAI) and soil water content (SWS) (Fig.1).
For some AD indices, there is both an upper and a lower limit that is independent of whether the climate of the area is arid or humid: vegetation health or soil water content are or are not frequently deteriorated or in deficit, respectively. In that sense, AD drought indices are relevant for any type of climate. However, SPI and most MD and HD indices, are statistical values showing a deviation from average and standardised for all climates. Even if they remain meaningful, drought is more challenging in dryer climates rather than wet climates. This key point is dismissed because of the statistical and standardising propensity of MD and HD indices, in contrast to the values of AD indices that are a practical interpretation of hydro-climatic features (e.g. of the reflectance, in the case of NDVI and LAI).

4.2 Socio-economic conditions

SSA combines the lowest number of studies about drought indices with the highest proportion in terms of drought impacts (Fig. 4). Even though SSA is known to experience a rise of temperatures and an increase of aridity in the past, present and future by observation and model projections (Niang et al., 2014; Serdeczny et al., 2017) the reported impacts in the Emergency Database (EM-DAT) are scarce (Harrington and Otto, 2020). Yet, the International Disaster Database (EM-DAT) run by the Centre for Research on the Epidemiology of Disasters (CRED), has the most complete and global records of past natural and human-made disasters events (Guha-Sapir et al., 2012).

Most of SSA is in a situation of economic water scarcity (Molden, 2013), implying a lack of human, institutional and financial capital to satisfy the demand for water, even in areas where the physical availability of water is not limited. The symptoms described by Molden (2013) associated to economic water scarcity include scant infrastructure development, either small or large scale, meaning that populations experience difficulties obtaining sufficient water to meet agricultural or domestic needs. Applying the same reasoning, drought mitigation or monitoring bodies and scientific publications are a product of human, institutional and financial capital. Thus, it is likely that drought drivers are under-investigated in SSA, leading to the same effects of economic water scarcity: water and food insecurities. Also, the report of impacts of extreme weather in SSA to disaster databases as EM-DATA are predominantly conducted by non-governmental organisations rather than governments, often as a side product of their main task to identify the location with the greatest need for humanitarian aid (Harrington and Otto, 2020).

In some areas, food insecurity can be a cumulative result of a dry climate and high pressure on natural resources enhanced by rapid demographic growth. Countries such as Bangladesh, China, Ethiopia, India, Indonesia and Pakistan, have some of the highest number of drought-related food security publications (Fig. 5). Most of these countries have high fertility rates and rapid population growth (United Nations, 2019; Vollset et al., 2020). According to the Food and Agriculture Organization (FAO (2010)), the majority of the world’s undernourished people live in these six countries and over 40% live in China and India alone. The same applies for the countries of SSA, presenting the highest population growth rate in the world (World Bank, 2019), the highest number of drought-related food security publications (Fig. 5), and 22% of the population being undernourished (FAO, 2019). A rapid population growth increases the challenge of adequately meeting nutritional needs as
food production depends on croplands and water supply, which are under strain as human populations increase. This suggests that countries with arid climates and a high demography are more exposed to food security impacts.

Moreover, populations of low income countries are the most exposed to drought-related food insecurity. In the world’s poorest countries, around 30 percent of GDP comes from agriculture; those countries are mostly concentrated around the Sahelian region: Mali (37.4% of GDP), Niger (35.4%), Chad (46.1%), Central African Republic (31.9%), Sudan (31.2%), Kenya (31.1%) and Ethiopia (34.7%) (World Bank, 2016). As we can see from Fig. 5 FS, those countries are most commonly reporting food security impacts related to drought. In contrast, in OECD economies – regarded as developed and high-income countries – agriculture accounts for less than 1.5 percent of GDP (World Bank, 2016). In the same way, we note the fewest amount of publications related to food security in those OECD countries. Also, in these Sahelian countries, agriculture accounts for more than 80% of the livelihoods (FAO, 2021). As more people rely on agriculture for their livelihood, they are more exposed to natural hazards like drought and thus vulnerable to food insecurity and the poverty trap.

4.3 Data availability

The SPI is the most widely used index in drought-related studies (Table 1 and Fig. 1). This can be explained by its ease of use: First, it only requires (monthly) precipitation data, easy to monitor by use of rainfall gauge networks or satellite estimation. Second, SPI reference values exist so they can be compared and are applicable in all climate regimes. Finally, SPI can be computed for different periods of time including periods of record containing missing-data, even though it ideally needs at least 30 years of monthly precipitation data (WMO, 2012).

However, all these strengths are at the same time weaknesses. The SPI will provide in all cases an output whatever inputs are used (Svoboda and Fuchs, 2016). As an example, a significant quantity of zero precipitation values at short time scales may lead to biased values of the SPI, because the rainfall might not fit for the recommended gamma distribution, which is a fundamental first step of the SPI calculation (Wu et al., 2007). This scenario is applicable to dry climates with a distinct dry season when calculated for periods shorter than 12 months. As mentioned in section 4.1, an index including an additional temperature parameter to account for evapotranspiration is more suitable for such areas. As we can see in Figure 6, many countries with dry climates (Iran, Australia and Pakistan) commonly use the SPI in their drought-related studies. In those dry contexts, it has been proposed to focus on the duration of the drought rather than only its severity (Wu et al., 2007). However, even short-lived dry spells often combined with heatwaves of a few days, characteristic of dry climates, when occurring during the reproductive stage of crop development can be enough to ravage an entire harvest leading to food insecurity (Hatfield and Prueger, 2015).
Most of the MD indices, beyond the SPI, are sensitive to the quantity and reliability of the data to fit the distribution. Their calibration requires a recommended 30 to 50 years of data. However, only very few regions of the world possess such an abundant historical hydrometeorological database. This is particularly challenging for developing countries. According to the World Bank (2018), two thirds of the hydrological observation networks in developing countries are reported to be in poor or declining condition. The distribution of rain gauges across SSA is eight times lower than the WMO minimum recommended level, and while coastal West and Southern Africa, and the East Africa Highlands of Kenya and Uganda are relatively well represented, areas of greater aridity are severely underrepresented (Walker et al., 2016). Consequently, reanalysis rainfall products are also less reliable for these more arid regions due to a lack of ground truthing data (Walker et al., 2016). The availability of data seems to be closely tied with the socio-economic condition of a country. As mentioned in Section 4.2, countries exposed to economic water scarcity generally experience a lack of capital to satisfy the demand for water and a lack of an extensive and well-maintained hydro-climatic monitoring network. Therefore, most of the countries of SSA are underrepresented or absent from publications related to drought indices, while high-income countries commonly report them (Fig. 5).

The same applies for HD indices studies that are under-reported in SSA (Fig 3, 4 & 5). River flow monitoring networks in SSA are experiencing a similar decline to meteorological monitoring networks (Walker et al., 2016). However, globally, little attention seems to be given to the monitoring of HD indices (Fig. 1 &2). One reason could be that a “hydrological” drought is
seen by many as a drought impact, and there is a demonstrable lack of extensive monitoring of drought impacts (Lackstrom et al., 2013; Pozzi et al., 2013; Wilhite et al., 2007).

As Table 1 shows, NDVI – a remotely sensed index – is the most commonly used in agricultural drought-related studies. Only 3 out of the 15 agricultural drought indices are not remotely sensed. Just like the HD indices, this can reflect (i) the lack of hydrometric (field) observations or (ii) if they exist, a lack of sharing and access to them (Bachmair et al., 2016). Bachmair et al. (2016) highlight how “the scarcity of water status observations, especially for groundwater, reflects the common focus on drought seen through the lens of rainfall and soil moisture that can be easily (remotely) monitored and/or modelled”. Indeed, the data needed to calculate AD indices seem more accessible. The most used index is the NDVI and requires land surface imagery containing both red and infrared bands and processing software; global NDVI datasets are available open source at relatively high spatiotemporal distributions. As there are no requirements for historical data for calibration or a monitoring network, this could explain why the African continent more prominently reports AD than MD and HD (Fig. 5).

It is important to realise that data availability may be closely tied to the year of implementation of the drought indices. Indeed, hydro-climatic databases have different ages and dataset quality according to the country, but it can also be possible that the implementation of drought indices is a precursor of hydro-climatic data monitoring.

### 4.4 Scientific interest and orientation

As mentioned previously, in DEWS, the indices linked to the three categories of drought are seen as drivers as they are used to determine the occurrence and severity of a drought. However, as shown in Sections 3 and 4.3, the distinction between drought drivers and impacts, based on hydro-climatic variables, is not always clear. First, the linear representation of drought implies that AD and HD are an impact of MD. Yet the indices used for MD have a different scope to those used for AD and HD. Taking the example of the most used indices, the SPI has a temporal focus with a strong statistical perspective on drought. Whereas for AD, the NDVI has a “spatial distribution” focus as it uses remote sensing to indirectly determine water-limitation in the vegetation at a specific time, like a snapshot of the vegetation health. In that sense, the NDVI measures a drought impact.

Moreover, water security is often confounded with hydrological drought. However, as we can see from Fig. 5d and Fig. 5e, the areas where each HD and WS are reported in scientific studies are not the same, suggesting that the occurrence of the first does not imply the other. In that sense, the literature seemingly indicates that HD is not the only driver of WS.

The scientific reporting about drought suggests its risk of occurrence in an area and potentially an initiative of preparation for related damages. Though for each country, it is likely that drought is investigated according to: (i) a determined scientific approach, more physical or social; (ii) a purpose, in the sense of what is at greatest risk of being impacted by drought.

As shown in Table 1, most of the drought-drivers indices are investigated under the domain of environmental, Earth and agricultural sciences, suggesting a more physically-based approach. Food and water securities related to drought, respectively more reported in SSA and in Australia-Oceania (Fig. 5), are also studied through the scope of physical sciences but unlike the drivers, also through the lens of social sciences (Table 1).
Food security is a complex concept that is looked at in a holistic way. Food systems underpin food security and they are the result of the production, processing, distribution, preparation and consumption of food. These steps are themselves the results of dynamic interactions between and within the bio-geophysical and human environments (Gregory et al., 2005). Thus, its study requires the intervention of different specialists. Food systems encompass three main components: “(i) food availability (with elements related to production, distribution and exchange); (ii) food access (with elements related to affordability, allocation and preference) and (iii) food utilisation (with elements related to nutritional value, social value and food safety)” (Gregory et al., 2005). Hence, when food systems are stressed, food security is affected. As food security depends on many components, it stands vulnerable to the disturbance of any of them. These components can be disturbed by a range of factors that can be environmental, like droughts, but also circumstantial like conflict, changes in international trade agreements and policies, HIV/AIDS (Gregory et al., 2005). Food insecurity can be enhanced when these factors are combined. SSA is an area particularly prone to extreme heat-related impacts, heatwaves, as we mentioned in Sect. 4.2, but also to these circumstances. SSA holds: (i) more than 95% of farmed land relying on rainfed agriculture (Wani et al., 2009); (ii) about 75% of the world HIV/AIDS prevalence as of 2016 (Odugbesan and Rjoub, 2019); (iii) 19 of the 43 economies with the highest poverty rate, all classified as in fragile and conflict-affected situations (Corral et al., 2020). Thus, food security related to drought studies in SSA may also be related to the implication of these social processes.

Australia, known to be the driest inhabited continent (Hill, 2004), has a “National Plan for Water Security” (Government of Australia, 2007) that comprises a variety of mechanisms addressed by national and state governments (Cook and Bakker, 2012). Water security is also aimed to be addressed in an integrative and multi-scale way by “taking action on climate change, using water wisely, securing water supplies and supporting healthy rivers and wetlands” (Government of Australia, 2007).

Besides Australia, the fact that water security is reported for countries with extreme differences in socio-economics, such as countries in the Sahel and the USA (Fig. 5), suggests the experience of different types of water security. The definition of “water security” by UN Water (2013) is quite holistic. A population’s access to adequate quantities of acceptable quality water has the goal to sustain three areas: livelihoods, human well-being, and socio-economic development (Montanari et al., 2013). Countries at different stages of development are more likely to focus on one of those three areas. Human well-being related to water-security can have many different understandings (Jepson et al., 2017; Hoekstra et al., 2018). Those can vary from one extreme to the other, as enough water for sanitary purposes, e.g. sanitation and showers, to indulgent leisure (e.g. swimming pools and gardens (Savelli et al., 2021; Bradley and Bartram, 2013; Willis et al., 2010)). In South Africa, experiences of Cape Town Day Zero’s water crisis were diametrically different amongst the wealthy elite and the township dwellers. The first went through restrictions to water their garden and fill up their swimming pools while the second had insufficient water to take showers and go to the toilet (Savelli et al., 2021). Livelihoods and socio-economic development can also be understood and applied in different ways: from subsistence farming (Makurira et al., 2011) to agrobusiness and irrigation of crops meant for export (e.g. California (Morris and Bucini, 2016)). The same can apply to food security: from malnutrition (Belesova et al., 2019) to the genetic adaptation of fruits and vegetable strains to droughts (Belesova et al., 2019; Basu et al., 2016).
Therefore, not only can areas be exposed to food and/or water insecurities, but they can be exposed to different declinations and severity within each. Water and food insecurities are very context specific, not even attributable to the country scale but to smaller areas. They are the result of complex and multi-disciplinary mechanisms, including social processes in addition to the physical ones. Thus, to be accurately monitored, drought-related water and food insecurities also need multi-disciplinary metrics. This comes in contradiction with drought indices that measure drought severity by looking only at the hydro-climatic component. Consequently, by eluding (the monitoring of) social processes that can trigger and enhance drought impacts, drought indices seem to be formulating an incomplete forecast of the severity of droughts.

4.5 Limitations

The inability to deduce a cause-and-effect relationship between two variables, solely on the basis of an observed association or correlation between them is common to all disciplines. The same applies for drought drivers and drought impacts even in drought prone areas. It is difficult to state if droughts are the cause of impacts, aggravator of existing impacts, or if those “impacts” were pre-existing conditions and not linked to the occurrence of drought events. Without continuous and widespread monitoring of drought impacts, the societal pattern enabling understanding of how drought is experienced differently and why, will not be identified. Therefore, the attempt of explaining the geographical repartition of drought-related impact studies by linking some features of drought to one or many of the four hypotheses detailed above, as per this study, remains then purely hypothetical.

Our approach separated studies by geography, principally at sub-continental scale. Other divisions on which to base our analysis could have been applied, like climatic or income levels, and may have led to additional insights. However, separating studies by geographical region allowed highlighting of: (i) both physical and socio-economic similarities expected in homogenous geographic areas; (ii) countries standing out. This enabled the investigation of potential justifications.

Disparities exist inside countries, where, for example, areas are wealthier than others or experience different climates. This applies particularly to larger countries such as the United States, China, Brazil and India. Therefore, it is possible that in some large countries, more prosperous areas might be centralising the background work and the studies on drought indices. It is also possible that physical, socio-economic, data availability and interest disparities may also exist inside countries. However, because our drought metrics investigation and analysis is at the country level, our discussion is also generalised to that scale. Getting rid of that aggregative propensity and grasping those regional disparities would have required an investigation at the scale of within-country regions (e.g.: California Central Valley, Brazilian semi-arid). Yet, it is mostly the name of the countries that are used in publications on Scopus. Moreover, that level of detail and analysis would be more appropriate for comparative studies between chosen semi-arid regions of the world rather than a broader study, like this one, where similar focus on drought and drought impacts indices are examined.

The studies we obtained and analysed were a result of using Scopus, rather than another abstract and citation database, and of how we formulated our queries. Our search was constrained to articles having their title, abstract and keywords in English,
potentially excluding important articles written in other languages. Additionally, the queries of the drought drivers were per indices, individually, while the queries of the impacts were regrouped by two themes. We justified the approach of grouping drought impacts keywords due to the lack of metrics existing for water and food insecurities related to drought, as is the case for drought drivers indices.

4.6 Recommendations

It has to be recognised and highlighted that DEWS have achieved the goal of providing timely and reliable information to decision makers for drought management and mitigation. The value of this study being to increase the relevance and utility of drought-related variables, we also acknowledge that the metrics they rely on are mostly conceptual and descriptive which contradicts their operational purposes. Their structure also tends to exclude the human influence on drought and drought influence on humans. The emphasis is on the natural effects on the hydrological system. Subsequently, the accuracy and efficiency of drought mitigation measures can be sub-optimal if it is based only on information lacking consideration of observed (local) drought impacts.

A recommendation would be to also consider a drought mitigation focus shifted on the optimal human welfare that drought is obstructing, rather than only measuring on which hydrosystem compartment there is a deficit. In humanitarian approaches, a human welfare approach makes sense as the addressed disaster damages, in the short and long-term, can adversely affect basic human safety through malnutrition, displacement, livestock or even human mortality. But this can also be applicable in drought management. Indeed, there is a lack of consensus in defining a drought and its impacts resulting in difficulty on agreeing on coherent and accurate drought metrics. Therefore, shifting the focus of drought mitigation to observable, graspable and quantifiable goals, such as human welfare, could overcome the uncertainty around drought and drought impacts definition.

In a drought mitigation perspective, the human welfare proxy could be considered as an optimal situation without water shortage, e.g. zero hunger, poverty, conflicts and water insecurity. Thus, it could be aligned with the Sustainable Development Goals (SDG) as they (i) represent the development priorities of both low- or high- income countries; (ii) benefit from existing and improvable metrics. Also, similarly to drought indices, SDGs have a global nature inclined to overlook the local context. By taking into account local particularities, the SDGs could be reached at the local level even it is through a drought mitigation scope. Instead of the linear and still conceptual driver-focused “meteorological-agricultural-hydrological” droughts, the disaster scope could shift to more societally relevant goals linked to “poverty, water security, and food security”. Thus, operational approaches of drought management would be the equivalent of determining the extent to which drought is hampering the achievement of one or many of these defined goals.

Some studies have already been arguing in favour of considering other approaches than the two main top-down and bottom-up approaches for climate change adaptation strategies (Ludwig et al., 2014; Conway et al., 2019). Both approaches come with their strengths and weaknesses and conciliating them represents a challenge and many complexities, often unsuitable for integrating into water management (Ludwig et al., 2014). The issues complicating the decision-making are well known: the
top-down approach is too broad and presents too much uncertainty; the bottom-up approach focuses too much on socio-economic vulnerability and too little on developing (technical) solutions (Ludwig et al., 2014). Thus, a risk-oriented approach that focuses more on “systems of receptors rather than conventional sectors” (Warren et al., 2018), where research identifies vulnerability to different extreme events rather than only analysing their probabilities of occurrence (Bliss and Bowe, 2011), is an alternative.

5 Conclusions
We conducted a bibliometric analysis on 5000+ scientific studies in which drought was associated to an index and water and food securities, with the aim of comparing how drought drivers (e.g. precipitation, temperature, evaporative demand) and drought impacts (food and water insecurities) were reflected in the literature. Our results revealed that drought is mainly depicted through a conceptual lens, focusing on precipitation-based and remotely sensed indices. It is the SPI, a single-variable index, that is the most broadly used in different climatic and geographic contexts, despite being the one including the least local contextual information. Drought is regularly approached merely as a rainfall statistical anomaly and equated to meteorological drought.

Drought drivers studies tend to focus on particular geographical regions, especially northern countries, whereas studies reporting impacts related to food and water securities are more commonly located in Sub-Saharan Africa and Australia-Oceania respectively. Moreover, the areas where drought drivers are reported in scientific studies are different from the drought impacts ones. There is also a difference in the geographic repartition of drought-related food security and water security scientific studies. This suggests that drought-impacts studies are certainly dependent on both the physical and human processes occurring in the geographic area, i.e. the local context.

Because “local context” can have different meanings, we raised four hypotheses that can be attributed to local context and that can contribute to drought drivers resulting in drought impacts. First, the physical availability of water; drought drivers indices measure the water deficit in one or several of the components of the hydrological cycle, implying that the severity of drought is the same in arid or humid climates. Second, the socio-economic conditions in the countries, as the income per capita and the demography that affect, respectively, the capital involved in research and the vulnerability to hazards. Third, the data availability, related to the second point concerning socio-economic conditions, affects the selection and accuracy of an index, especially if the chosen index is unsuitable for the particular climate. Fourth, the scientific approach and the interest in the country that determines from which physical and/or social sciences scope drought will be looked at and for what purpose. It seems that drought impacts are considered more through social sciences lenses than drought drivers. Drought drivers indices seem to remain conceptual metrics depicting climate features and do not seem to be linked to human-centered solutions. Also, both water and food securities are scientific concerns mostly in arid and semi-arid regions, from high to low income and whether drought drivers are investigated or not. This suggests many variants of the same type of impact according to what or who is likely to be most impacted by drought in the area.
Thus, more research is needed where the scope of drought mitigation is widened to the vulnerability to drought events rather than only their probability of occurrence. DEWS would then more accurately predict the severity of a drought by also including drought indices that are people-centered. In this way, drought metrics would also better align with SDSs. These drought metrics could become more useful in monitoring the negative role of drought in achieving human welfare, and with that, the SDGs.

### Appendices

| “M/A/H drought” Indices mentioned in the study | Acronym | Query |
|-----------------------------------------------|---------|-------|
| Standardized Precipitation Index              | SPI     | TITLE-ABS-KEY ( ("Drought") AND ("SPI" OR "Standardized Precipitation Index") ) |
| Standardized Precipitation Evapotranspiration Index | SPEI   | TITLE-ABS-KEY ( ("Drought") AND ("SPEI" OR "Standardized Evapotranspiration Index") ) |
| Aridity Index                                | AI      | TITLE-ABS-KEY ( ("Drought") AND ("Aridity Index") ) |
| Precipitation Deciles                         | Deciles | TITLE-ABS-KEY ( ("Drought") AND ("Precipitation Decile" OR "rainfall decile") ) |
| Keetch-Byram Drought Index                    | KBDI    | TITLE-ABS-KEY ( ("Drought") AND ("Keetch-Byram Drought Index" OR "KBDI") ) |
| Palmer Drought Severity Index                 | PDSI    | TITLE-ABS-KEY ( ("Drought") AND ("Palmer Drought Severity Index" OR "PDSI") ) |
| Percent of Normal Precipitation (Index)       | PNPI    | TITLE-ABS-KEY ( ("Drought") AND ("Percent of Normal Precipitation" OR "Percent of Normal Precipitation Index" OR "PNPI") ) |
| Rainfall Anomaly Index                        | RAI     | TITLE-ABS-KEY ( ("Drought") AND ("Rainfall Anomaly Index" OR "RAI") ) |
| Self-Calibrated Palmer Drought Severity Index | scPDSI  | TITLE-ABS-KEY ( ("Drought") AND ("Self-Calibrated Palmer Drought Severity Index" OR "sc-PDSI") ) |
| Crop Moisture Index                           | CMI     | TITLE-ABS-KEY ( ("Drought") AND ("Crop Moisture index" OR "CMI") ) |
| Evaporative Stress Index                      | ESI     | TITLE-ABS-KEY ( ("Drought") AND ("Evaporative Stress Index" OR "ESI") ) |
| Evapotranspiration Deficit Index              | ETDI    | TITLE-ABS-KEY ( ("Drought") AND ("Evapotranspiration Deficit Index" OR "ETDI") ) |
| Index                                                  | Key                                                                 |
|-------------------------------------------------------|----------------------------------------------------------------------|
| Enhanced Vegetation Index                             | EVI TITLE-ABS-KEY (( "Drought") AND ( "Enhanced Vegetation Index" OR "EVI")) |
| Normalized Difference Vegetation Index                | NDVI TITLE-ABS-KEY (( "Drought") AND ("Normalized Difference Vegetation Index" OR "NDVI" )) |
| Leaf Area Index                                       | LAI TITLE-ABS-KEY (( "Drought") AND ( "Leaf Area Index" OR "LAI")) |
| Palmer Moisture Anomaly Index – known as the Palmer Z index | PZI TITLE-ABS-KEY (( "Drought") AND ( "Palmer Z Index" OR "Palmer Moisture Anomaly Index" OR "PZI" )) |
| Soil Adjusted Vegetation Index                        | SAVI TITLE-ABS-KEY (( "Drought") AND ( "Soil Adjusted Vegetation Index" OR "SAVI" )) |
| Soil Moisture Anomaly                                 | SMA TITLE-ABS-KEY (( "Drought") AND ( "Soil Moisture Anomaly" OR "SMA" )) |
| Soil Moisture Deficit Index                           | SMDI TITLE-ABS-KEY (( "Drought") AND ( "Soil Moisture Deficit Index" OR "SMDI" )) |
| Soil Water Deficit Index                              | SWDI TITLE-ABS-KEY (( "Drought") AND ( "Soil Water Deficit Index" OR "SWDI" )) |
| Soil Water Storage                                    | SWS TITLE-ABS-KEY (( "Drought") AND ( "Soil Water Storage" OR "SWS" )) |
| Vegetation Condition Index                            | VCI TITLE-ABS-KEY (( "Drought") AND ( "Vegetation Condition Index" OR "VCI" )) |
| Vegetation Drought Response Index                     | VegDRI TITLE-ABS-KEY (( "Drought") AND ( "Vegetation Drought Response Index" OR "VegDRI" OR "Veg DRI" )) |
| Vegetation Health Index                               | VHI TITLE-ABS-KEY (( "Drought") AND ( "Vegetation Health Index" OR "VHI" )) |
| Reservoir Level                                       | TITLE-ABS-KEY (( "Drought") AND ( "Reservoir level" OR "water level in reservoir" OR "water levels in reservoirs" )) |
| Palmer Hydrological Drought Index (PHDI)              | PHDI TITLE-ABS-KEY (( "Drought") AND ( "Palmer Hydrological Drought Index" OR "PHDI" )) |
| Streamflow Drought Index                              | SDI TITLE-ABS-KEY (( "Drought") AND ( "Streamflow Drought Index" OR "SDI" )) |
| Standardized Runoff Index                             | SRI TITLE-ABS-KEY (( "Drought") AND ( "Standardized Runoff Index" )) |
| Standardized Streamflow Index                         | SSFI TITLE-ABS-KEY (( "Drought") AND ( "Standardized Streamflow Index" OR "SSFI" )) |
| Streamflow anomaly                                    | TITLE-ABS-KEY (( "Drought") AND ( "streamflow anomaly" )) |
| Standardized Water-level Index                        | SWI TITLE-ABS-KEY (( "Drought") AND ( "Standardized Water Level Index" OR "SWLI" )) |
TABLE A 1: Table of queries used in the advanced search of Scopus to retrieve the scientific studies of the drought indices and impacts.

| Surface Water Supply Index (SWSI) | TITLE-ABS-KEY ("Drought" AND ("Surface Index" OR "SWSI")) |
|-----------------------------------|-------------------------------------------------------------|
| **Drought impacts studies**       |                                                              |
| Food security                     | TITLE-ABS-KEY("drought" AND ("food secur*" OR "food insecu*" OR "famine" OR "hunger" OR "hidden hunger" OR "malnourish*" OR "undernourish*" OR "malnutrition" OR "undernutrition" OR "crop loss*" OR "yield loss*" OR "agricultural loss*" OR "agricultural product loss*" OR "loss of agricultural land*")) |
| Water security                    | TITLE-ABS-KEY ("drought") AND ("safe") AND ("water access" OR "drinking water") OR ("clean") AND ("drinking water" OR "drinking source") OR "freshwater availability" OR "water secur*" OR "water insecu*" OR "water crisis") |

445 **Code and data availability**

Both code and data are available in the 4tu.ResearchData platform. The link of access is [https://figshare.com/s/dd10a23059dd637464bf](https://figshare.com/s/dd10a23059dd637464bf) The doi is: [https://doi.org/10.4121/14452845.v2](https://doi.org/10.4121/14452845.v2)

**Author contribution**

450 SK has designed and conducted the research in collaboration with DWW, supervised by LAM and PRvO. SK has written the manuscript with input from all co-authors. The final version has been approved by all co-authors.

**Competing interests.**

Authors have declared no competing interests.

**Acknowledgements**

455 This work is part of the research program Joint SDG Research Initiative with project number 07.30318.016, which is (partly) financed by the Dutch Research Council (NWO) and the Interdisciplinary Research and Education Fund (INREF) of Wageningen University, the Netherlands.
We thank Germano Gondim Ribeiro Neto, Louise Cavalcante de Souza Cabral, Petra Hellegers and Eduardo Sávio Passos Rodrigues Martins that reviewed and provided helpful comments on earlier drafts of the manuscript.

We thank the anonymous reviewers whose comments and suggestions helped improve and clarify this manuscript.

References

Addor, N., and Melsen, L. A.: Legacy, Rather Than Adequacy, Drives the Selection of Hydrological Models, Water Resources Research, 55, 378-390, https://doi.org/10.1029/2018WR022958, 2019.

Aria, M., and Cuccurullo, C.: bibliometrix: An R-tool for comprehensive science mapping analysis, Journal of informetrics, 11, 959-975, 2017.

Bachmair, S., Stahl, K., Collins, K., Hannaford, J., Acreman, M., Svoboda, M., Knutson, C., Smith, K. H., Wall, N., Fuchs, B., Crossman, N. D., and Overton, I.: Drought indicators revisited: the need for a wider consideration of environment and society, Wiley Interdisciplinary Reviews: Water, 3, 516-536, 10.1002/wat2.1154, 2016.

Basu, S., Ramegowda, V., Kumar, A., and Pereira, A.: Plant adaptation to drought stress, F1000Res, 5, F1000 Faculty Rev-1554, 10.12688/f1000research.7678.1, 2016.

Belesova, K., Agabirwe, C. N., Zou, M., Phalkey, R., and Wilkinson, P.: Drought exposure as a risk factor for child undernutrition in low- and middle-income countries: a systematic review and assessment of empirical evidence, Environment international, 131, 104973, 2019.

Bliss, K. E., and Bowe, K. F.: Bridging Knowledge Gaps in Water Management: Integrating Approaches to Food, Water, Energy, and the Environment, Center for Strategic and International Studies, 2011.

Bradley, D. J., and Bartram, J. K.: Domestic water and sanitation as water security: monitoring, concepts and strategy, Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 371, 20120420, 2013.

Brazilian Drought Monitor: http://monitordesecas.ana.gov.br/mapa?mes=3&ano=2021, access: 26th of April 2021, 2021.

Conway, D., Nicholls, R. J., Brown, S., Tebboth, M. G. L., Adger, W. N., Ahmad, B., Biemans, H., Crick, F., Lutz, A. F., De Campos, R. S., Said, M., Singh, C., Zarouq, M. A. H., Ludi, E., New, M., and Wester, P.: The need for bottom-up assessments of climate risks and adaptation in climate-sensitive regions, Nature Climate Change, 9, 503-511, 10.1038/s41558-019-0502-0, 2019.

Cook, C., and Bakker, K.: Water security: Debating an emerging paradigm, Global Environmental Change, 22, 94-102, https://doi.org/10.1016/j.gloenvcha.2011.10.011, 2012.

Corral, P., Irwin, A., Krishnan, N., Mahler, D. G., and Vishwanath, T.: Fragility and Conflict: On the Front Lines of the Fight against Poverty, The World Bank, 2020.

The International Disaster Database: http://www.emdat.be/, access: 31 March 2020, 2021.

FAO: The state of food insecurity in the World 2010, Addressing food insecurity in protracted crises, WFP, FAO. Journal of Rural Studies, 29, 101-112, 2010.

Country fact sheet on food and agriculture policy trends: http://www.fao.org/in-action/fapa/publications/country-fact-sheets/en/, access: 26th of April 2021, 2021.

FAO, L. UNICEF, WFP, WHO: The state of food security and nutrition in the world 2019: safeguarding against economic slowdowns and downturns. Rome, Italy: FAO, 2019.

Government of Australia: A national plan for water security, Canberra, 2007.

Gregory, P. J., Ingram, J. S. I., and Brklacich, M.: Climate change and food security, Philos. Trans. R. Soc. B Biol. Sci., 360, 2139-2148, 10.1098/rstb.2005.1745, 2005.

Guha-Sapir, D., Vos, F., Below, R., and Ponserre, S.: Annual disaster statistical review 2011: the numbers and trends, 2012.

Harrington, L. J., and Otto, F. E. L.: Reconciling theory with the reality of African heatwaves, Nature Climate Change, 10.1038/s41558-020-0851-8, 2020.

Hatfield, J. L., and Prueger, J. H.: Temperature extremes: Effect on plant growth and development, Weather and Climate Extremes, 10, 4-10, https://doi.org/10.1016/j.wace.2015.08.001, 2015.

Hill, R. S.: Origins of the southeastern Australian vegetation, Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences, 359, 1537-1549, 2004.

Hoekstra, A. Y., Buurman, J., and van Ginkel, K. C. H.: Urban water security: A review, Environmental Research Letters, 13, 053002, 10.1088/1748-9326/aaba52, 2018.

Jepson, W., Budds, J., Eichelberger, L., Harris, L., Norman, E., O'Reilly, K., Pearson, A., Shah, S., Shinn, J., and Staddon, C.: Advancing human capabilities for water security: A relational approach, Water Security, 1, 46-52, 2017.

Kchouk, S., Melsen, L. A., and Van Oel, P. R.: Data underlying the publication: “A review of drought indices: predominance of drivers over impacts and the importance of local context”. Water Resources Management Group, W. U. R. (Ed.), 2021.
Van Loon, A. F., Gleeson, T., Clark, J., Van Dijk, A. I. J. M., Stahl, K., Hannaford, J., Di Baldassarre, G., Teuling, A. J., Tallaksen, L. M., Uijlenhoet, R., Hannah, D. M., Sheffield, J., Svoboda, M., Verbeiren, B., Wagener, T., Rangecroft, S., Wanders, N., and Van Lanen, H. A. J.: Drought in the Anthropocene, Nature Geoscience, 9, 89-91, 10.1038/ngeo2646, 2016.

Vogt, J. V., Naumann, G., Masante, D., Spinoni, J., Cammalleri, C., Erian, W., Pischke, F., Pulwarty, R., and Barbosa, P.: Drought Risk Assessment and Management, 2018.

Vollset, S. E., Goren, E., Yuan, C.-W., Cao, J., Smith, A. E., Hsiao, T., Bisignano, C., Azhar, G. S., Castro, E., and Chalek, J.: Fertility, mortality, migration, and population scenarios for 195 countries and territories from 2017 to 2100: a forecasting analysis for the Global Burden of Disease Study, The Lancet, 396, 1285-1306, 2020.

Walker, D., Forsythe, N., Parkin, G., and Gowing, J.: Filling the observational void: Scientific value and quantitative validation of hydrometeorological data from a community-based monitoring programme, Journal of Hydrology, 538, 713-725, https://doi.org/10.1016/j.jhydrol.2016.04.062, 2016.

Wani, S. P., Rockström, J., and Oweis, T. Y.: Rainfed agriculture: unlocking the potential, CABI, 2009.

Warren, R. F., Wilby, R. L., Brown, K., Watkiss, P., Betts, R. A., Murphy, J. M., and Lowe, J. A.: Advancing national climate change risk assessment to deliver national adaptation plans, Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 376, 20170295, 2018.

Wilhite, D. A., and Glantz, M. H.: Understanding the drought phenomenon: the role of definitions, Water international, 10, 111-120, 1985.

Wilhite, D. A.: Drought as a natural hazard: concepts and definitions, 2000.

Wilhite, D. A., Svoboda, M. D., and Hayes, M. J.: Understanding the complex impacts of drought: A key to enhancing drought mitigation and preparedness, Water Resources Management, 21, 763-774, 10.1007/s11269-006-9076-5, 2007.

Willis, R. M., Stewart, R. A., Panuwatwanich, K., Jones, S., and Kyriakides, A.: Alarming visual display monitors affecting shower end use water and energy conservation in Australian residential households, Resources, Conservation and Recycling, 54, 1117-1127, https://doi.org/10.1016/j.resconrec.2010.03.004, 2010.

WMO: Standardized Precipitation Index User Guide (M. Svoboda, M. Hayes and D. Wood), Geneva, Switzerland, 2012.

Agriculture, forestry, and fishing, value added (% of GDP): https://data.worldbank.org/indicator/NV.AGR.TOTL.ZS?end=2019&name_desc=true&start=1960&type=shaded&view=map&year=2016, access: 12th of February, 2016.

World Bank: Assessment of the state of hydrological services in developing countries, International Bank for Reconstruction and Development/The World Bank, Washington DC 2018.

World Bank: Population growth (annual %) - World: https://data.worldbank.org/indicator/SP.POP.GROW?locations=1W&name_desc=false&view=map, access: 4th of March, 2019.

Wu, H., Svoboda, M. D., Hayes, M. J., Wilhite, D. A., and Wen, F.: Appropriate application of the standardized precipitation index in arid locations and dry seasons, International Journal of Climatology, 27, 65-79, 10.1002/joc.1371, 2007.

Zargar, A., Sadiq, R., Naser, B., and Khan, F. I.: A review of drought indices, Environmental Reviews, 19, 333-349, 10.1139/a11-013, 2011.