Received: 13 June 2019 | Revised: 6 November 2019 | Accepted: 19 November 2019

DOI: 10.1002/wat2.1407

OVERVIEW

WIREs WATER WILEY

Drought: Progress in broadening its understanding

Gebremedhin Gebremeskel Haile[1,2,3] | **Qiuhong Tang**[1,2] | **Wenhong Li**[4] | **Xingcai Liu**[1] | **Xuejun Zhang**[5]

[1]Key Laboratory of Water Cycle and Related Land Surface Processes, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing, China

[2]University of Chinese Academy of Sciences, Beijing, China

[3]Tigray Agricultural Research Institute, Mekelle, Ethiopia

[4]Earth and Ocean Sciences, Nicholas School of the Environment, Duke University, Durham, North Carolina

[5]China Institute of Water Resources and Hydropower Research, Beijing, China

Correspondence

Qiuhong Tang, Key Laboratory of Water Cycle and Related Land Surface Processes, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing, China.
Email: tangqh@igsnrr.ac.cn

Funding information

International Partnership Program of Chinese Academy of Sciences, Grant/Award Number: 131A11KYSB20170113; National Natural Science Foundation of China, Grant/Award Numbers: 41790424, 41425002; Strategic Priority Research Program of Chinese Academy of Sciences, Grant/Award Number: XDA20060402

Abstract

Drought affects many aspects of society and its impact is global. To this end, rendering recurrent drought occurrences is a key research focus. Recently, in addition to existing knowledge, progress in scientific advancements regarding drought have been observed on a regional and global scale. Here, we reviewed and outlined current and emerging scientific developments in drought, focusing on progress made in recent years. In the human-modified world, the anthropogenic effects on drought were dominant and drought-frequency showed a prominent increase. In this study, we have identified the development of drought concepts, types, and indices, and their indicators were developed as sector-specific, comprehensive, and oriented towards multiple scales. Anthropogenic changes have enhanced hydrological processes and affected the development of drought. Urbanization, deforestation, and related human activities have aggravated drought. Climate change has had an exacerbating role in drought, which is expected to increase during the 21st century. Human communities, in particular, are undertaking activities that cause droughts; suffering from and coping with their impact. In addition, the direct and indirect effects of drought need reconsideration. As such, the health impact of droughts is a concern in drought-vulnerable societies and its burden on public health is largely unknown. The need for drought recovery to aid in effective ecosystem functioning in the aftermath of the drought and the development of mitigation measures to alleviate recurrent drought is critical. Enhanced drought monitoring and management options are required under existing environmental and socioeconomic setups in the 21st century.

This article is characterized under:

Science of Water > Water Extremes

Engineering Water > Planning Water

Water and Life > Stresses and Pressures on Ecosystems

KEYWORDS

Anthropocene, carbon cycle, drought indices, drought recovery, flash drought, public health

1 | INTRODUCTION

Drought affects many aspects of society and its impact is global. According to the United Nations, drought is the "most far-reaching of all-natural disasters" on Earth (United Nations, 2018). It is an assuredly fatal and disastrous hazard for living beings and the environment (AghaKouchak, 2015; Nicholson, 2014). The direct impacts of drought are wide ranging; specifically, it jeopardizes the environment, economy, social security, agriculture, water, energy, tourism, ecosystems, and basic human welfare, leading to displacement and death (AghaKouchak, Feldman, Hoerling, Huxman, & Lund, 2015; Bachmair et al., 2016; Bond, Lake, & Arthington, 2008; Dai, 2011; Muller, 2014; Stagge, Kohn, Tallaksen, & Stahl, 2015; Van Loon et al., 2016). Drought has affected each continent in various spatiotemporal situations (Sheffield, Andreadis, Wood, & Lettenmaier, 2009). For example, the complex impact of drought over several years in regions such as the Sahel and East Africa were devastating (Benson & Clay, 1998; Mao et al., 2017; Moorhead et al., 2015). As a result, drought-related losses have been registered throughout recorded history (Mo & Lyon, 2015; Solh & van Ginkel, 2014; Van Loon, 2015).

Drought also has an indirect impact on health problems including wildfires, dust, and vector-borne disease (Berman, Ebisu, Peng, Dominici, & Bell, 2017; Smoyer-Tomic, Klaver, Soskolne, & Spady, 2004). As public health is driven by an aggregate of direct and indirect drought exposures, it presents a chronic environmental exposure, causing increased stress and mental health issues. These effects exert an increased impact on human beings that have so far been ignored. To this end, the multifaceted hydrological effects of drought require comprehensive drought-adapting capacities to aid societal and environmental well-being.

Drought usually occurs naturally, but can be aggravated by multiple natural/climatic and anthropogenic drivers (Below, Grover-Kopec, & Dilley, 2007; Mishra & Singh, 2010; Mukherjee, Mishra, & Trenberth, 2018; Sheffield et al., 2014). Climate variability, anthropogenic impact, climate changes, and land-use changes, intensified by topographic complexities accelerate intense and frequent drought events (AghaKouchak, Feldman, et al., 2015; Herrera-Estrada, Satoh, & Sheffield, 2017; Van Loon, Gleeson, et al., 2016, Van Loon, Stahl, et al., 2016; Zhao & Dai, 2015). Drought is often triggered by dynamic interaction between the atmosphere and land surface, which alters water fluxes such as precipitation, evaporation, and evapotranspiration over a longer duration (AghaKouchak, Feldman, et al., 2015; Pekel, Cottam, Gorelick, & Belward, 2016; Sheffield & Wood, 2008a, 2008b; Zhao, Velicogna, & Kimball, 2017). Similarly, frequent and severe droughts are observed and projected at global and regional scales for various reasons. These include acute shortage of natural water resources, rapid population growth, concentration of people in urban areas, residence in semi-arid regions, and globalization of food markets (AghaKouchak, Feldman, et al., 2015; Gocic & Trajkovic, 2014; Van Loon, Gleeson, et al., 2016; Van Loon, Stahl, et al., 2016).

Development of drought involves interplay between various climate processes as well as land–atmosphere feedback in the climate system, especially under global warming. Natural climate variabilities and increased levels of greenhouse gases often combine to cause enhanced warming with low atmospheric humidity and cloud cover in the atmosphere (Van Loon & Van Lanen, 2013; Van Loon, Gleeson, et al., 2016; Van Loon, Stahl, et al., 2016). This complex interplay results in precipitation deficit and hence the development of meteorological drought over time (Herrera-Estrada et al., 2017; Van Loon, 2015). Through nonlinear propagation mechanisms, meteorological drought further evolves to agricultural and then to hydrological drought (Mukherjee et al., 2018; Van Loon, Van Huijgevoort, & Van Lanen, 2012). The shifting of water deficits in different forms from one to another type of drought is mainly governed by climate and catchment characteristics (Van Loon & Van Lanen, 2013). As the shifting/propagation mechanism reaches hydrological drought, the drought becomes severe and harder to recover from within a short period of time. Hence, understanding of drought propagation dynamics and their influencing factors are required for early drought adaptation and mitigation measures.

Drought frequency is observed to have increased globally, although with substantial regional variation (Dai, 2011). For example, the frequency and intensity of drought have increased over East Asia, the Mediterranean, and West Africa, but decreased in central North America and north-west Australia since the 1950s (Dai, 2011; Hartmann et al., 2013). Droughts have become more common, especially in the tropics and subtropics, since the 1970s (Hartmann et al., 2013; Sheffield, Wood, & Roderick, 2012). Moreover, global warming is expected to increase by a factor of two and six for drought occurrence and duration, respectively, by the end of the 21st century (Burke, Brown, & Christidis, 2006; Sivakumar et al., 2014; Trenberth et al., 2014). Drought is likely to set in more quickly and intensely under the increased heating from global warming (Trenberth et al., 2014). This trend will increase in the future as society's demands on water and environmental services increase. Thus, there is a pressing need to improve drought prediction and forecasting to build more plausible drought early warning, planning, and preparation systems. Records of past spatial distribution and temporal evolution of drought conditions could help to achieve reliable future drought forecasting. The increased data availability of remote sensing products, reanalysis data, and land surface models has been utilized in drought analysis along with ground-truth gauge data (AghaKouchak, Farahmand, et al., 2015). Additionally, drought modeling, spatiotemporal analysis, use of global and regional climate models, and land data assimilation systems based on future scenarios are invaluable in drought forecasting (Hao, Singh, & Xia, 2018). However, data availability, quality, and lengths of records remain issues in drawing reliable, drought predictions on a global scale (Hartmann et al., 2013). In addition, lack of in situ measurement networks, seasonal forecast skills, and the capacity to translate data into usable information has hindered drought forecasting facilities, especially in non-developed countries (Pozzi et al., 2013).

Drought is an elusive phenomenon and its adaptation and mitigation are difficult (Bachmair et al., 2016). As a result, an investigation into drought needs to be conducted to address the possible consequences of drought via various drought alleviation strategies. In recent decades, drought mitigation and monitoring have become increasingly crucial (Van Loon, 2015). Comprehensive involvement of stakeholders is of utmost importance for the alleviation of drought. Regional and global collaborations are needed for more adaptation to and management over possible future droughts. Therefore, understanding how drought is evolving could have a practical significance in ensuring food security and sustainable regional development via mitigating drought effects. Drought research that focuses on the most vulnerable regions has manifold advantages. Various studies have been undertaken to investigate different aspects of drought conditions. As a result, the study results have been used by people, governments, and stakeholders for drought monitoring and management. Advancement in understanding the behavior of drought both globally and in a specific region of interest is also inevitable. This is important for applying new knowledge and techniques for taking drought mitigation measures.

Various papers have reviewed drought and addressed several issues regarding drought concepts, identification, classification, and quantification (e.g., Dai, 2011; Hao & Singh, 2015; Mishra & Singh, 2010, 2011; Sheffield & Wood, 2012; Van Loon, 2015). However, these literature reviews do not include relevant publications from the last 10 years, a period in which drought research has developed rapidly. For example, a series of health effects associated with drought have been identified (Berman et al., 2017; Vins, Bell, Saha, & Hess, 2015) but are not included in the earlier review papers. A comprehensive review of drought hydrology has not been reported in recent years. The objectives of this paper are to: (a) provide an overview of the findings of drought studies in the last decade; (b) highlight the different types, indicators, and predictions of droughts; and (c) provide advice for future drought research. To further deliver recent information and techniques on drought mitigation, we provide detailed illustrations by reviewing the relevant literature. While reviewing, we consider various drought research results complemented by methods, systems, and approaches used in the literature. In addition, drought indicators are used to clearly present the available knowledge on drought issues and concepts.

This review paper is organized as follows: Section 1, Introduction; Section 2, Drought definitions and concepts; Section 3, Development of drought types and indicators; Section 4, Assessment of drought in the Anthropocene; Section 5, Drought impact of socio-environmental systems and its mitigation; and finally, Conclusions in Section 6.

2 | DROUGHT DEFINITIONS AND CONCEPTS

Due to a multitude of effects and aspects of drought, a universally accepted drought definition does not exist (Esfahanian et al., 2017; Hayes, Svoboda, Wall, & Widhalm, 2011; Lloyd-Hughes, 2014). However, the scientific community has defined different types of drought based on drought classifications, characterizations, and multiple perspectives (Tokarczyk, 2013).

The simple definition of drought is a deficit of water compared with normal conditions (Sheffield & Wood, 2012). According to the Intergovernmental Panel on Climate Change (2007), drought is defined in general terms as a "prolonged absence or marked deficiency of precipitation," a "deficiency of precipitation that results in a water shortage for some activity or for some group," or a "period of abnormally dry weather sufficiently prolonged for the lack of precipitation to cause a serious hydrological imbalance." The shortage of natural availability of water can be in the atmosphere, which is usually expressed as precipitation; in the land, indicated as soil moisture; at river streams, explained as flowing water; or in the subsurface, explained as groundwater. A social drought is often caused due to an imbalance between the society's supply of and demand for water (Calow, MacDonald, Nicol, & Robins, 2010; Hao & Singh, 2015). Water shortages can also occur in reservoirs, lakes, and groundwater levels, which may lead to increased competition for water (Seneviratne et al., 2012).

Drought is a multivariate/multiscalar event, so it has to be defined using various statistical techniques, such as different indices, mean, median, and percentiles on spatiotemporal scales (Mishra & Singh, 2010). Moreover, drought is usually characterized by its duration, magnitude, intensity, and spatial extent (Hao & Singh, 2015; Mishra & Singh, 2011), which is essential for spatiotemporal drought analysis. Drought is thus described mostly by hydro-meteorological variables called drought indicators, which are often used to derive drought indices (Bachmair et al., 2016). For example, the likelihood of drought has been discussed based on the existence of one or more of the following factors: late onset, erratic distribution, and early cessation of rainfall; prevailing hot surface temperatures; higher dry winds; and low relative humidity (Hao & Singh, 2015).

In the Anthropocene, a new definition of drought was introduced based on the causes of drought, including the following three concepts: (a) climate-induced drought, caused by climate variability; (b) human-induced drought, caused by human influence on the water cycle; and (c) human-modified drought, caused by a combination of climate variability and human influence on the water cycle (Van Loon, Stahl, et al., 2016).

Drought should not be confused with aridity, low flow, water scarcity, or desertification, which is common in the arid and semi-arid regions worldwide. Low flows are associated with low river discharge often characterized by annual minimum flow series (Van Loon & Laaha, 2015). Sometimes drought and aridity are perceived to have the same meaning, even though they do not. Indeed, although drought and aridity both indicate water deficiency, aridity is a constant and relatively permanent climatic feature while drought exhibits temporary behavior (NISDR, 2009). The concept of water scarcity is also different from drought, as the former is related to water supply shortage due to anthropogenic influences on the water system (Seneviratne et al., 2012). Desertification is used to denote dry climate or land dryness as a result of extended dry periods, which results in losing water bodies, vegetation, and wildlife (Kassas, 1987; Kéfi et al., 2007). Usually, drought aggravates desertification (Kassas, 1987). Drought does not only occur during a period that is relatively dry, but also during water shortages in a given climate condition (Tallaksen & Van Lanen, 2004). Based on the illustrations briefed so far, drought by itself constitutes a science. Hence, the concepts of drought have widespread phenomenal aspects. As a result, contemporary studies use the term “drought hydrology” in the scientific community.

3 | DEVELOPMENT OF DROUGHT TYPES AND INDICATORS

3.1 | Conceptual framework on drought types and indicators

The study of drought has shown multidirectional development. The cause–impact–resilience of drought takes place on the environment, aggravated by anthropogenic effects (Figure 1). Although the natural/climate variability and anthropogenic effects are the main driving forces behind drought occurrence, society's impact on the environment has shown a greater role in the recurrence of drought in the human-modified world. Society and the environment have a role throughout the process, underlying the interlinkages and interactions between various drought conditions. The way drought is characterized is also shown to include relevant variables from different perspectives. Figure 2 illustrates the conceptual diagram of the existing and new developments related to drought. Drought types have become sector-specific, while drought indices showed multiscalar and integrated development. Drought also has different impacts on various sectors, including agriculture, water resources, and human health. Meanwhile, drought monitoring and management, such as drought mitigation and recovery, has resilient power. Real-time drought forecasting complemented by higher resolution datasets facilitates better preparedness for an early warning of drought. Generally, new developments and/or changes of droughts are highly influenced by human actions on the environment.

3.2 | Types of drought and indicators

Different types of drought were derived as a result of various hydro-meteorological variables, commonly called drought indicators or indices (Bachmair et al., 2016). As a result, droughts have been categorized based on various characteristics, from which the drought type is derived. Van Loon (2015) discussed hydrological droughts from water shortages in rivers, lakes, and groundwater and their development and recovery focused more on drought indicators with a wider consideration of the environment and society. Considering these works, our paper provides a review in order to broaden the understanding of new and existing changes or developments in various areas related to drought.

The most common types of drought are meteorological, agricultural, and hydrological. These are the general types from which other emerging drought types such as socio-economic, ecological, groundwater, and stream health droughts are developed. Strong links between meteorological, hydrological, and agricultural droughts are found by studying the

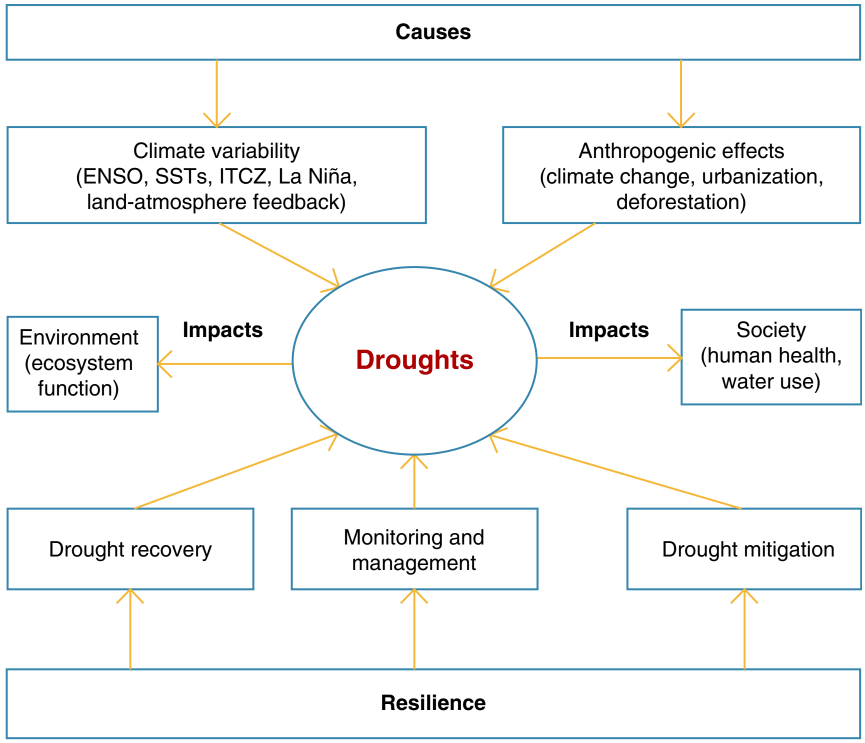

FIGURE 1 Conceptual diagram illustrating the cause, impacts of and resilience to drought. Note: ENSO, El Niño/Southern Oscillation; SSTs, sea surface temperatures; ITCZ, Inter-Tropical Convergence Zone. Boxes indicate the different aspects of drought. Yellow arrows show linkages from one aspect of drought to the other indicating cause–effect relationships

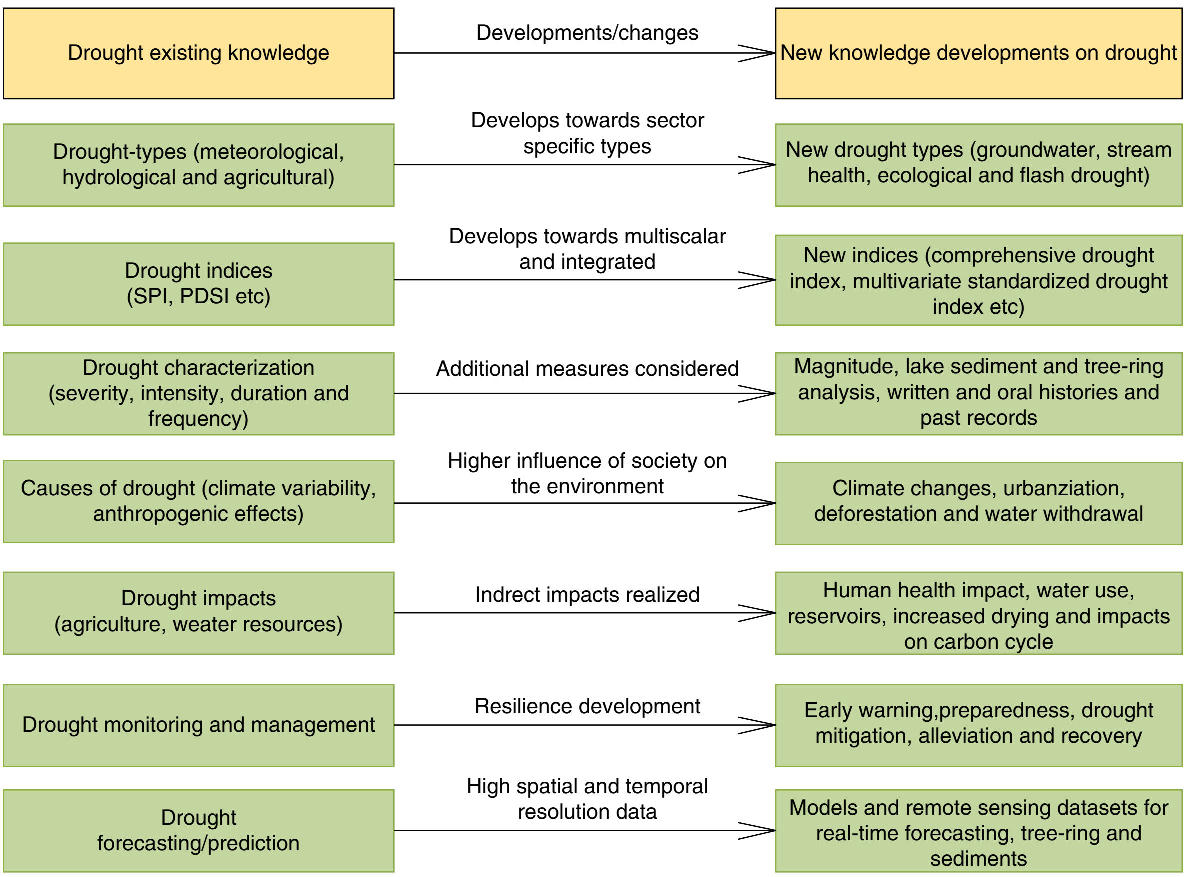

FIGURE 2 Illustration of the drought developments and changes as influenced by human activities in the Anthropocene

various aspects of drought characteristics. Hence, a separate and integrated assessment of these drought types would be of paramount importance globally.

3.2.1 | Meteorological drought

Meteorological/climatological drought (or precipitation deficit) is a period ranging from months to years of below-normal rainfall, accompanied by above-normal temperatures (Lyon et al., 2012). A meteorological drought occurs due to multiple climatic causes. It is also associated with weather systems (such as high-pressure systems) and climate feedbacks that result in minimal precipitation (Bergman, Ropelewski, & Halpert, 1986; Karl & Young, 1987; Wei et al., 2019).

Meteorological drought is mainly quantified by precipitation deficit, measured by drought indices such as the standardized precipitation index (SPI) and standardized precipitation evapotranspiration index (SPEI; Vicente-Serrano, Beguería, & López-Moreno, 2010). The World Meteorological Organization recommended the use of the SPI to national meteorological and hydrological agencies for the determination of meteorological drought events (Hayes et al., 2011; Hayes, Svoboda, Wardlow, Anderson, & Kogan, 2012; Sheffield et al., 2014; Yoon, Mo, & Wood, 2012). Hence, the SPI has been routinely used to classify meteorological drought by national and international forecast centers and authorities (Yoon et al., 2012). Similarly, the SPEI is used to monitor meteorological drought by considering the water balance in the hydrological cycle (Vicente-Serrano et al., 2010). SPEI has the advantage of combining multiscalar character with the capacity to include the effects of temperature variability in drought assessment (Vicente-Serrano et al., 2010). The SPI and SPEI range from extremely dry to extremely wet, with zero as the boundary between wet and dry conditions (Zhu, Wang, Singh, & Liu, 2016).

As meteorological data are easily measured, in situ meteorological station data are widely used to establish drought indices for drought monitoring. Hence, meteorological drought prediction is commonly performed based on a medium- to long-range climate forecast on precipitation using a variety of statistical methods (Yoon et al., 2012). Seasonal forecasts for meteorological drought are usually made for between 3 and 6 months depending on the season, location, and precipitation data (Mo & Lyon, 2015). The monthly or seasonal drought forecast is useful for drought mitigation, agricultural planning, and management.

3.2.2 | Hydrological drought

Another important drought category is hydrological drought, which occurs when river streamflow and long-term surface and sub-surface water resources decline from their long-term average levels (Tallaksen & Van Lanen, 2004; Tokarczyk, 2013; Van Loon & Laaha, 2015). Streamflow, the hydrological variable, is commonly used to measure the occurrence and impact of hydrological drought. The hydrological drought is determined by mean annual precipitation deficit and catchment elevation governed by the climate control system (Van Loon & Laaha, 2015). Hence, hydrological drought can be defined as a lack of water in the hydrological system, manifested in abnormally low streamflow in rivers, lakes, and reservoirs (Tallaksen & Van Lanen, 2004; Tokarczyk, 2013; Van Loon, 2015). Moreover, a hydrological drought could cover extensive areas and last for months to years (Sheffield et al., 2012).

Efficient consideration of meteorological drought is vital to studying the immediate occurrence and development of hydrological drought happening over a specific area. The available literature on hydrological drought reveals the multitude of processes underlying its development and recovery in the hydrological system (Schwalm et al., 2017; Tokarczyk, 2013; Van Loon, 2015). The occurrence of hydrological drought is complex, involving atmospheric processes and their variabilities, catchment characteristics, and terrestrial hydrological system variations (Zhao et al., 2017). Hydrological drought severity is mainly explained by climate and catchment characteristics (Van Loon & Laaha, 2015). The former indicates that a lack of precipitation directly causes meteorological drought, and the latter denotes the catchment's inability to catch and store the water (Tallaksen & Van Lanen, 2004). Both help us to understand how hydrological drought persists in the hydrological system through propagating into extensive areas along with their drainage networks. Thus, hydrological drought duration and severity are governed by a combination of climate and catchment control (Van Loon & Laaha, 2015). Hydrological drought is preceded by atmospheric/meteorological drought conditions and is associated with "drought propagation" (Tallaksen & Van Lanen, 2004; Tokarczyk, 2013), denoting the change of the drought signal as meteorological drought moves through the terrestrial part of the hydrological cycle (Van Loon et al., 2012; Van Loon & Laaha, 2015). This propagation feature is controlled by catchment characteristics and the climate system of the area of investigation (Grayson & Bloschl, 2001; van Lanen, Fendeková, Kupczyk, Kasprzyk, & Pokojski, 2004). Moreover, the spatial pattern of the hydrological drought is patchy as it is dependent on local catchment characteristics and underlying terrestrial hydrological processes (Grayson & Bloschl, 2001). Hence, the spatial variation of hydrological drought (duration and severity) is highly dependent on terrestrial hydrological processes. In line with this, Huang et al. (2017) found that the propagation time from meteorological to hydrological drought has seasonal characteristics.

3.2.3 | Agricultural drought

Agricultural/vegetative/soil moisture drought is the prevalence of dry soils, as a result of below-average precipitation and/or above-normal evaporation (Tallaksen & Van Lanen, 2004). Agricultural drought, in short, is the lack of moisture in the soil profile or plant root zone. Soil moisture is depleted when lack of rainfall, evapotranspiration/evaporation, groundwater drainage, and stream runoffs persist (Van Loon, 2015). If agricultural drought lasts for many years, it creates a devastating effect on livelihoods dependent on agriculture (Muller, 2014).

Among the drought types, agricultural drought is most easily detected, as it has a direct and clear association with the limited growth or failure of crops due to a shortage of rainfall/water in a specific area. To quantify agricultural drought, soil moisture content (mostly in the root zone) is usually used as the main input variable (Mao et al., 2017). It has a direct impact on reducing crop production and plant growth if the soil is not in a state of field capacity. Soil moisture plays a crucial role in the water supply to crops during non-rainfall periods (Sheffield et al., 2009; Zhao et al., 2017), and is a vital hydrological variable with respect to understanding agricultural drought via various complementary drought components (Mao et al., 2017). Similarly, soil moisture is a comprehensively used variable in various climate, vegetation, and soil property studies (Kim, 2010; Wu & Kinter, 2009). However, application of a drought index based on soil moisture is often limited as the moisture content is observed very sparsely either in situ or via remote sensing. An effective index for agricultural drought is required to describe the process of drought initiation, development, and alleviation. Moreover, integrating the distributed hydrological models and appropriate drought indices is also vital in monitoring and early warning of agricultural drought events (Pozzi et al., 2013).

For data-poor or non-data regions, soil moisture can be simulated by hydro-climatological models from remote sensing products (AghaKouchak, Farahmand, et al., 2015; Mao et al., 2017). Applications of remotely sensed data are becoming popular for quantifying soil moisture, thereby quantifying agricultural drought. Remote sensing data are an alternative to in situ soil moisture data on large scales due to the improved spatial coverage, and the method is considered fast and economical (Scaini, Sánchez, Vicente-Serrano, & Martínez-Fernández, 2015; AghaKouchak, Farahmand, et al., 2015). With the development of satellite remote sensing technology, relevant drought studies have been carried out using remote sensing data (e.g., soil moisture, precipitation, and temperature). Satellite-based soil moisture projects include the Scatterometer (Wagner et al., 2013), the Soil Moisture and Ocean Salinity satellite (Kerr et al., 2001), and the Climate Change Initiative soil moisture project (Hollmann et al., 2013). The Soil Moisture Anomaly Percentage Index (SMAPI) was established for agriculture drought identification and for investigation of drought spatiotemporal characteristics (Mao et al., 2017). The SMAPI plays an important role in recommending crop water supply and is a key factor in the rapid assessment of agricultural drought events.

Remote sensing data, however, can only provide soil moisture data in the thin upper layers due to the influence of vegetation and other factors (AghaKouchak, Farahmand, et al., 2015; Wu, Lu, Wen, & Lin, 2011). The soil moisture profile is important for understanding agricultural drought, as a significant amount of water approaches plant roots through the capillary rise. Distributed hydrological models provide soil moisture at both the surface layer and in deep soil, and thus are becoming an effective tool to study agriculture drought occurrences and intensity at different spatial and temporal scales. For example, through remote sensing techniques, Mao et al. (2017) quantified agricultural drought by applying a semi-distributed macro-scale hydrological model: the Variable Infiltration Capacity. The model simulates soil moisture so that the drought index can be established for drought assessment (Sheffield et al., 2014; Wang et al., 2018).

3.3 | Emerging types of drought and indicators

3.3.1 | Socio-economic drought

Beyond the commonly known drought types, socio-economic drought (Mishra & Singh, 2010; Shi, Chen, Wang, & Niu, 2018) is a newly recognized drought type, which is associated with supply and demand of water to a society (Mishra & Singh, 2010). This type of drought occurs when the supply of water is too limited to fulfill the demand, usually caused by the impacts of agricultural, hydrological and meteorological droughts (Van Loon, 2015). Shi et al. (2018) propose a new heuristic method and a new index, the socio-economic drought index, to identify and evaluate socio-economic drought events of different severity levels (i.e., slight, moderate, severe, and extreme) in the context of climate change.

3.3.2 | Flash drought

Flash droughts are short term, rapidly evolving drought events during crop growing seasons, occurring simultaneously with unusually high temperature (Yuan, Ma, Pan, & Shi, 2015). These droughts can be characterized by a rapidly developing drought event with extreme heat, low soil moisture, and high evapotranspiration (Ford, McRoberts, Quiring, & Hall, 2015; Mo & Lettenmaier, 2015; Yuan et al., 2015). Flash droughts occur concurrently with strong heatwaves that exacerbate drought conditions, and vice versa (Wang, Yuan, Xie, Wu, & Li, 2016). Moreover, flash droughts have rapid onsets, unusual intensity, and devastating impacts on crop yields and water supply (Wang et al., 2016). For example, during the 2012 Central US flash drought, high temperatures and depletion of soil moisture rates caused severe damage to crops, with huge economic losses. In China, flash droughts increased by 109% from 1979 to 2010 mainly due to long-term warming of temperatures, increasing evapotranspiration, and decreasing soil moisture (Wang et al., 2016).

Flash droughts have specially defined characteristics compared to traditional types of drought. Unlike in conventional droughts, high evapotranspiration rates, caused by anomalously high temperatures, winds, and incoming radiation are usually present before the onset of flash droughts (Chen et al., 2019). Otkin et al. (2018) suggested that more focus should be given to the rate of intensification than to duration, as a flash drought develops at an unusually rapid rate of intensification compared to other drought types. Specifically, flash droughts fall within the category of agricultural drought as they have a direct link to soil moisture variations. As a result, soil moisture observations have been consistently used for identifying the rapid onset of flash droughts (Ford et al., 2015).

Two types of flash drought with different nomenclatures exist (Mo & Lettenmaier, 2016; Wang & Yuan, 2018; Zhang, Tang, Liu, Leng, & Li, 2017; Zhang, You, Chen, & Li, 2017). Wang and Yuan (2018) investigated high-temperature-driven (Type I) and water-deficit-driven (Type II) flash drought types over China. Similarly defined heatwave flash droughts (e.g., 2012 Central US flash drought) as having high temperatures with rapidly decreasing soil moisture, due to increased evapotranspiration, with soil moisture in deficit at the onset of the drought event. The second type of flash drought is precipitation-deficit flash drought, caused by precipitation deficits which in turn cause evapotranspiration to decrease and temperature to increase (Mo & Lettenmaier, 2016). Type I flash droughts occur when increased temperature causes the evapotranspiration to increase and soil moisture to decrease before onset, whereas an intensified soil moisture deficit, decreased evapotranspiration, and increase in temperature occurs before the onset of Type II droughts (Wang & Yuan, 2018). Type I occurs over southern China, where moisture supply is sufficient, whereas Type II occurs over the semi-arid regions of northern China, with soil moisture deficit (Wang & Yuan, 2018; Zhang, Tang, et al., 2017; Zhang, You, et al., 2017). In the US, heatwave flash drought events last only for 1–2 pentads, while precipitation-deficit flash droughts can reach values greater than three pentads (Mo & Lettenmaier, 2015). In contrast, in China, Type I flash droughts vary from 5 to 8 pentads, while Type II reach up to 4 pentads (Wang & Yuan, 2018).

The simultaneous occurrence of warm temperature and droughts has increased globally in the context of climate change. These lead to an accelerated drying trend of soil moisture and increased evapotranspiration, which leads to increased flash droughts especially during warming hiatus (Wang et al., 2016). In addition, anthropogenic warming increases the probability of concurring warm or dry conditions impacting human and natural ecosystems, as observed in the 2012–2014 California drought (Diffenbaugh, Swain, & Touma, 2015). In China, anthropogenic warming may exacerbate future flash drought conditions, most likely over humid and semi-humid regions such as southern and north-eastern China (Wang et al., 2016; Zhang, Tang, et al., 2017; Zhang, You, et al., 2017). Moreover, in South Africa, flash droughts have tripled due to anthropogenic climate change over the last 60 years and were intensified during the 2015–2016 heatwaves (Yuan et al., 2018). These suggest that human activities have increased the probability of warm climates under the conditions of low-precipitation years (Diffenbaugh et al., 2015). To capture the rapid onset of flash droughts substantiated by anthropogenic activities, it is necessary to generate drought intensification forecasts by developing better forecasting techniques and improvements to climate models (Otkin et al., 2018). Hence, for early warning systems suitable for the rapidly evolving nature of flash droughts, in situ soil moisture observations are an important source of information in detecting flash drought events (Ford et al., 2015).

3.3.3 | Groundwater drought

Another very important, but often overlooked, drought type is groundwater drought (Van Lanen & Peters, 2000). Groundwater drought occurs when droughts impact groundwater systems such as groundwater recharge, groundwater levels, and groundwater discharge, and cause them to decrease over a period of months to years (Van Lanen & Peters, 2000). Lack of precipitation is the main cause of this drought, because rainfall deficit usually leads to decreased groundwater recharge aggravated by groundwater abstractions for irrigation, domestic, and industrial uses and its overexploitation (Mishra & Singh, 2010). Groundwater drought happens when a clear decrease of groundwater level occurs over an area (Eltahir & Yeh, 1999). Groundwater drought is not a common phenomenon, but when it happens, it often shows long periods of below-normal groundwater levels and is very unlikely to recover quickly (Schwalm et al., 2017; Van Loon & Laaha, 2015).

3.3.4 | Stream health and ecological drought types

Stream health drought (Esfahanian et al., 2016), defined as a period of time where streamflow deficiency causes irreversible impacts on aquatic/riverine ecosystems, is another important drought type. Monitoring of this drought type uses index flow, stream size, and stream temperature to capture information on the vulnerability of fish to drought.

Moreover, Crausbay et al. (2017) proposed ecological drought, which helps to understand how drought affects ecosystems and the benefits they provide to society. This new drought type integrates the ecological, climatic, hydrological, socio-economic, and cultural dimensions of drought. Ecological drought is defined as an episodic deficit in water availability that drives ecosystems beyond thresholds of vulnerability, impacts ecosystem services, and triggers feedbacks in natural and/or human systems (Crausbay et al., 2017). Ecological drought is useful for fully addressing the ecological dimensions of drought behavior.

3.4 | Drought indices and their development

To better monitor and quantify drought, various drought indices have been developed. At present, more than 150 drought indices exist (Berman et al., 2017; Heim, 2002; Mishra & Singh, 2010). These indices have been developed as a function of various hydro-meteorological variables explained as drought indicators. These variables include rainfall, surface air temperature, soil moisture, evapotranspiration, river flow, and groundwater levels. A drought index usually measures a departure of the drought variable from the normal condition of the water/moisture levels. Examples of drought indices are the SPI (McKee, Doesken, & Kleist, 1993), SPEI (Vicente-Serrano et al., 2010), Palmer Drought Severity Index (PDSI; Palmer, 1965), Surface Water Supply Index, Reconnaissance Drought Index (Tsakiris & Vangelis, 2005), and Copula-based Joint Deficit Index (Kao & Govindaraju, 2010). Other examples include the Rainfall Anomaly Index (Van Rooy, 1965), Deciles, Crop Moisture Index (Palmer, 1968), National Rainfall Index (Gommes & Petrassi, 1994), and Reclamation Drought Index (Weghorst, 1996). Moreover, the Soil Moisture Drought Index (SMDI; Hollinger, Isard, & Welford, 1993), Crop-Specific Drought Index (Meyer & Hubbard, 1995), and Vegetation Condition Index (Liu & Kogan, 1996) can also be mentioned among others. Different reviews are made for these indices, which include descriptions of their drawbacks and strengths (e.g., Hao & Singh, 2015; Heim, 2002).

The performances of different drought indices correspond to the predefined drought types and spatial locations. For example, the Rainfall Deciles, Computed Soil Moisture, and Total Water Deficit drought indices showed the best performance among the meteorological, agricultural, and hydrological drought indices, respectively, in the United States (Keyantash & Dracup, 2002). Developments in drought indices are also evolving from using univariate to multivariate variables by applying in situ measurements, land surface simulations, and remote sensing products (AghaKouchak, Farahmand, et al., 2015; Hao & Singh, 2015). These have been witnessed to help policymakers in operational drought planning, preparedness, and mitigation efforts (Steinemann, Hayes, & Cavalcanti, 2005).

Drought indices are categorized as standardized or threshold-based indices (Van Loon, 2015). The standardized indices represent anomalies from a normal situation in a standardized way. These indices measure the departure of the water levels from normal conditions of the hydro-meteorological variables from each index (Dai, 2011). Examples are the SPI, PDSI, Standardized Groundwater-Level Index, SMDI (Palmer Z-Index), and Palmer Hydrological Drought Index. For the threshold-based indices, however, the drought characteristics are derived from time series of observed or simulated values of the hydro-meteorological variables using a pre-defined threshold level (Fleig, Tallaksen, Hisdal, & Demuth, 2006). This threshold level is considered with the drought-impacted sectors/systems (Van Loon & Laaha, 2015), for example, irrigation water requirements, drinking water supply, reservoir operation levels, or environmental flows to support stream ecology. Both the standardized indices and threshold-based indices analyze the drought categories, that is, meteorological, agricultural, and hydrological or other drought types, at different spatiotemporal scales.

For computation, drought indices use an individual indicator variable or combinations of many drought variables. To calculate drought indices, use of undisturbed, good-quality observational data is crucial. To compute the indices, data on the drought variables are obtained either from ground measurements or from satellites. Observational data sources such as meteorological stations, discharge gauging stations, groundwater wells, grid-based reanalysis data, and satellite data are useful (Van Loon, 2015). However, data records are often not adequate because some variables are missing, the data quality is poor, or some observations have been influenced by human activities (Van Loon, 2015). For instance, some reanalysis precipitation datasets showed uncertainties in depicting drought based on its severity, spatial pattern, and temporal persistence (Zhan, Guan, Sheffield, & Wood, 2016). Under such circumstances, it is preferable to use an ensemble of large-scale, physically based models and land surface models such as from the Water Model Intercomparison Project (Haddeland et al., 2011; Van Loon et al., 2012). Multiple data sources, such as satellite remote sensing products, are very useful for comprehensive drought characterizations using drought indices (AghaKouchak, Farahmand, et al., 2015). More advancements in drought indices involve incorporating remote sensing data assumed to understand the drought conditions in remote areas where observed data are scarce. Satellite remote sensing datasets provide high spatial resolution and real-time inland forecasts of the water cycle components (Tang et al., 2016; Tang, Gao, Lu, & Lettenmaier, 2009), and thus are preferable in regions where in situ observations are limited (AghaKouchak, Farahmand, et al., 2015; Sheffield et al., 2014). However, satellite data sources and newly developed drought indices require validation. Usually, validation of drought indices using ground-truth data is challenging, especially in remote areas where the drought mechanisms are lacking. Hence, drought indices validation uses comparison with well-accepted drought indices such as SPI or PDSI (Hao & Singh, 2015). Another drought index validation technique is to use past and current drought events for qualitative comparison.

Drought indices are still in development. Niemeyer (2008) suggested different categories of drought indices, named comprehensive, combined, and remote sensing, due to continuing developments in drought hydrology. Esfahanian et al. (2017) have developed a new combined drought index called the Comprehensive Drought Index (MASH) using meteorological, agricultural, stream health, and hydrological aspects of drought. In the MASH index, precipitation, streamflow, and evapotranspiration are the most influential variables from the hydrological, meteorological, and agricultural drought categories. Modifications to existing drought indices have also been made for better monitoring of drought events via mitigation and early warning (Bachmair et al., 2016; Pozzi et al., 2013). For example, Zhang et al. (2018) proposed a modified version of the Multivariate Standardized Drought Index (MSDI), that is, the Modified Multivariate Standardized Drought Index (MMSDI), based on precipitation, evapotranspiration, and soil moisture data. Results indicated that the MMSDI detected observed droughts in terms of drought intensity and drought-affected area, but the SPEI and Standardized Soil Moisture Index failed to do so. Moreover, the non-parametric multivariate, multi-index drought monitoring frameworks are becoming highly accepted in drought monitoring and management (Hao & AghaKouchak, 2014; Zhang et al., 2018). Nonetheless, further understanding and development of drought indices are vital for effective control of drought impacts. This would be beneficial in improving the scientific understanding of the drought phenomenon, its causes, impacts, and changes in time and space (Van Loon, 2015). Even though dozens of drought indices are available in each drought category, no single index is universally accepted among the existing indices (Hayes et al., 2011). Therefore, efforts should be exerted to find a consensus and formulate a unique, all-inclusive, universally accepted drought index.

In recent decades, public health issues associated with drought has gained more attention, although there is no index designed for this purpose (Berman et al., 2017; Smoyer-Tomic et al., 2004). A new drought index is needed urgently to capture the public health aspects affected by drought. This would solve challenges in the estimation of human exposure to drought and its health effects and benefit the policymakers and society for better drought early warning and alleviation.

4 | ASSESSMENT OF DROUGHT IN THE ANTHROPOCENE

4.1 | Drought characterization

Drought characterization is critical to understanding past and future drought, and for putting forward possible measures for its mitigation. Drought characterization is often achieved either by various parameters used in hydrological and climatological studies, or a combination thereof. For drought characterization/identification, threshold values of various statistical parameters, that is, drought characterizing factors, are useful (Figure 3). In drought characterization, drought indices work mainly alongside the drought characterizing factors. According to Dai (2011), drought can be characterized by its intensity, timing, duration, and/or spatial extent/coverage. Beyond the duration and severity (or intensity), a drought magnitude is added as a factor for drought characterization (Mishra & Singh, 2010). In addition, Schwalm et al. (2017) defined drought events, which could help in characterizing drought. Drought events are defined using a multiscalar drought metric in which a more negative value for a specific drought index indicates more severe drought relative to average long-term conditions. A drought event begins when a specific drought index is less than −1 for at least three consecutive months and ends when it becomes greater than −1 (Schwalm et al., 2017). According to Mishra and Singh (2010), drought duration is the occurrence of a drought parameter continuously below the critical level expressed in terms of years/months/weeks. Drought duration is associated with the length of time the drought has occurred for, which may be several months to a few years or beyond. It usually indicates a cumulative deficiency of a drought parameter below the critical level. Similarly, drought intensity is the average value of a drought parameter below the critical level, measured as a drought severity per its duration. Intensity is the individual or communal severity level of precipitation, soil moisture, or water storage deficit. Drought intensity is also expressed by the number of standard deviations from the long-term mean (Van Loon & Laaha, 2015). In addition, drought frequency (how often a drought occurs) and drought severity (the strength of a drought) are important in characterizing a drought event, as both have a direct relation to its impacts (Hayes et al., 2011). Drought magnitude is another characteristic parameter, which indicates the positive sum of the drought index (e.g., SPI, PDSI) for all the months within a drought event (Morid, Smakhtin, & Moghaddasi, 2006).

Beyond the above methods, understanding past drought events are of paramount importance for real drought characterization. Critical observation of tree rings (Woodhouse & Overpeck, 1998), sediments, and rocks (Mishra & Singh, 2010) in association with their climatic climax is useful for understanding and characterizing historical drought events. Moreover, the association of drought with atmospheric circulation patterns via atmospheric teleconnections is helpful for understanding the variability of oceanic and atmospheric parameters and their impacts for drought occurrences (Mishra & Singh, 2010). Beyond lake sediment analysis and tree-ring chronologies, the written and oral histories and

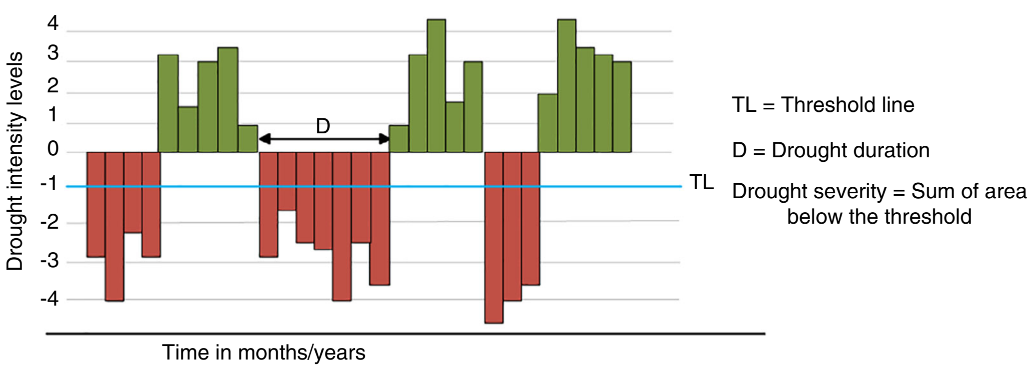

FIGURE 3 Illustration of the drought characteristics using its duration, severity and intensity at different timescales. *X*-axis: years/months (black line), *Y*-axis: drought intensity levels and the blue line represents a threshold line. Drought events refer to those years/months that a given drought index value is below the threshold line

past records of global climate change models are important for characterizing drought (Masih, Maskey, Mussá, & Trambauer, 2014).

4.2 | Drought forecasting/prediction

Drought has been recognized as one of the most widespread and expensive of natural disasters (Crausbay et al., 2017; Sheffield et al., 2012; Stagge et al., 2015) that requires precautionary actions. When drought occurs, huge losses of socio-economic resources occur due to lack of timely response strategies via accurate drought early warning information (Zhang, Tang, et al., 2017; Zhang, You, et al., 2017). Accurate forecasting of drought and its characteristics are needed to provide timely information to policymakers, water managers, and the general public (Van Loon, 2015). In addition, accurate forecasting of drought helps to improve the readiness of drought risk management, prevention, and mitigation measures (Hao et al., 2018). For drought early warning, planning, and preparation, real-time accurate tracking and predicting of the evolution of drought before it has occurred is necessary. This relies on drought forecast skills based on knowledge of initial conditions such as soil moisture, groundwater, and ocean–atmosphere teleconnection (e.g., El Niño/Southern Oscillation) (Zhang, Tang, et al., 2017; Zhang, You, et al., 2017). Decision support systems for drought forecasting are also emerging as useful tools in terms of issuing early warnings, assessing risk, and taking precautionary measures. As different factors exert direct and indirect influences on the occurrence of drought events, quantification and prediction of drought is challenging (DeChant & Moradkhani, 2015; Tang et al., 2009, 2016; Touma, Ashfaq, Nayak, Kao, & Diffenbaugh, 2015). Hence, drought forecasting is often interlinked with decision support systems for the implementers and users on the ground.

Over the past few decades, significant improvements have been made in drought forecasting (Mishra & Singh, 2011). Advancements in hydrological models provide a promising basis for near-future nowcasts and seasonal forecasts via real-time monitoring. Drought is usually predicted on the basis of monthly or seasonal forecasts using climatic variables. Statistical, dynamical, and hybrid methods are commonly employed for drought prediction (Hao et al., 2018). Hence, probabilistic drought forecasting events, spatiotemporal analysis, use of global and regional climate models, and land data assimilation systems based on existing and future scenarios have been developed and used for forecasting and monitoring of drought (Hao et al., 2018).

Lessons from past hydroclimatic patterns are vital, as future drought occurrences are difficult to predict with certainty (Cumani & Rojas, 2016). Hence, it is necessary to consider previous drought information to forecast the occurrence of drought in the future. Documentary evidence and historical documents provide valuable information on the direct and indirect impacts of drought on society, and societal responses to the environmental stresses (Brázdil, Kiss, Luterbacher, Nash, & Řezníčková, 2018).

Apart from in developed countries like the United States, drought forecasting poses challenges due to the lack of in situ measurement networks, seasonal forecast skills, and capacity to translate data into usable information (Pozzi et al., 2013). As a result, improvement in the seasonal forecasting of drought is a prerequisite for adequate operational water management (e.g., reservoir operation or irrigation abstractions) and other sectors.

4.3 | Drought in the human-modified world

In the human-modified world, that is, Anthropocene (Van Loon, Gleeson, et al., 2016), human influences on drought have increased (AghaKouchak, Feldman, et al., 2015; Van Loon, Gleeson, et al., 2016; Van Loon, Stahl, et al., 2016). The potential feedbacks between drought and society need to be included due to the human role in mitigating or enhancing drought. Anthropogenic changes in land surface alter hydrological processes and affect the development of drought (Van Loon, Gleeson, et al., 2016).

The 2014–2017 drought in Brazil can be regarded as a human-modified drought that resulted from deforestation, urbanization, reservoir construction, and climate variations (Van Loon, Gleeson, et al., 2016, Van Loon, Stahl, et al., 2016). Moreover, the recent severe droughts experienced in California, China, Spain, and Australia are associated with human-dominated environments (i.e., water stress as a result of urbanization, greenhouse gas emissions, and food and energy production) (AghaKouchak, Feldman, et al., 2015; Van Loon, Stahl, et al., 2016). These results indicate that the role of human activities is an integral part of drought to consider.

Growing water demand in large cities and agricultural areas have posed profound challenges to human water consumption in the Anthropocene (Wan et al., 2017). In the 21st century, droughts have been increasingly exacerbated by human demand for water (Crausbay et al., 2017). Water extraction in urban and irrigation areas intensifies future droughts and may lead to large catastrophes for society and the environment. In addition, human beings are drought victims driven by the complex interactions between natural and anthropogenic processes (Van Loon, Gleeson, et al., 2016). Human activities are responsible for causing drought, and human beings suffer from its impact and in coping with it. Different strategies need to be designed to achieve water sustainability, such as a reduction in water demand, water pricing policies, water use restrictions, increasing the efficiency of water used, and reuse (Wan et al., 2017).

In addition to natural climate variability, the increased human influences on the environment are leading to more intensified drought events (Haile et al., 2019; Jaeger et al., 2019; Margariti, Rangecroft, Parry, Wendt, & Van Loon, 2019). Marvel et al. (2019) provided historical evidence of human influences in global droughts since the early 20th century (1900–2005). This first-of-its-kind study found "fingerprints" confirming the connection between climate change and droughts globally. This linked trends in global drought patterns to human activities, revealing that anthropogenic actions could continue to influence droughts in the context of climate change (Marvel et al., 2019; Samaniego et al., 2018). For instance, Samaniego et al., 2018 revealed that anthropogenic warming is exacerbating soil moisture droughts in Europe. Anthropogenic climate change has altered the European river and streamflow discharges, suggesting increased water scarcity in renewable freshwater resources (Gudmundsson, Seneviratne, & Zhang, 2017). Similarly, anthropogenic activities have increased drought termination phases in the Anthropocene, leading to further consequences of drought impacts (Margariti et al., 2019). Specifically, in California, the severe 2011–2015 drought affected ozone air quality by potentially altering the ozone-forming organic reactivities, which showed a decrease by more than 50%, and influenced ozone air pollution (Demetillo et al., 2019). Compared to the 1.5 K Paris target, an increase of 3 K increases the drought area by 40%, affecting up to 42% of the European population (Samaniego et al., 2018). In addition, the historical American southwest multidecadal "megadroughts" have become a notable climatic feature for which Steiger et al. (2019) provided the first comprehensive theory, suggesting the first paleoclimatic evidence that the "megadroughts" were likely to increase with global warming. In the absence of effective mitigation, anthropogenic warming is anticipated to face an unprecedented increase in drought events in the future (Samaniego et al., 2018). Under complex human–natural systems, drought management needs efficient policies effective at conserving water to mitigate water shortages, provided the timing and location of conservation and shortages are matched (Jaeger et al., 2019). Hence, human influence on drought is likely to continue verifying the accuracy of climate models that could provide better drought predictions, which are important for decision-makers and society.

To accommodate the influences of anthropogenic activities during the Anthropocene, different methods have been used to analyze droughts. The use of historical meteorological datasets, such as rain and temperature measurements as well as satellite-based soil moisture datasets, have been increasingly applied recently (Marvel et al., 2019; Samaniego et al., 2018). Similarly, tree rings, sediments and rocks, vapor pressure deficit data, remotely sensed vegetation greenness, and higher resolution models are the main methods used to analyze/predict droughts (Anderegg et al., 2015; Mishra & Singh, 2010; Stocker et al., 2018, 2019; Xiao et al., 2009). A more robust benchmark decadal forecast skill by an elasticity framework can also be used to predict the global terrestrial water storage variabilities that are useful for understanding the status of a drought (Zhu, Yuan, & Wood, 2019).

4.4 | Climate change impacts and projection of future drought

There is a rising risk of drought in the 21st century (Crausbay et al., 2017). It is believed that droughts are expected to increase in frequency, severity, and duration in the future (Seneviratne et al., 2012; Wang et al., 2018). Climate change is blamed for the increased drought via decreased regional precipitation and increased evapotranspiration (Dai, 2011; Sheffield & Wood, 2008a, 2008b). This has led to a recent increase in the temporal and spatial occurrence of drought regionally and globally. More frequent and severe droughts are expected in the 21st century across many regions (Dai, 2011; Sheffield et al., 2012; Trenberth et al., 2014). However, regional variations are large. In China, for example, changes in drought severity, duration, and frequency suggest that meteorological, agricultural, and hydrological droughts will become more severe, prolonged, and frequent in the near future (Leng, Tang, & Rayburg, 2015).

In addition, climate change has an exacerbating role in causing droughts to become quicker, more intense, and longer-lasting (Schwalm et al., 2017; Trenberth et al., 2014). The increased heat from global warming may not cause droughts by itself, but when drought occurs, it may set in more quickly and intensely (Dai, 2011; Sheffield et al., 2012).

In addition, climate change has enhanced the severity and variability of drought (Wang et al., 2018) due to global warming, and this will greatly threaten future socio-economic development endeavors. Under climate change, human water consumption will also intensify the hydrological drought in the future. Significant changes in hydrological drought are due to increased temperature and potential evapotranspiration, and decrease in precipitation (Wang, Hejazi, Cai, & Valocchi, 2011). By far, water scarcity is becoming the greatest challenge of the 21st century (United Nations, 2018). Moreover, according to the United Nations report, about 1.8 billion people will experience water scarcity, two-thirds of the world will face water shortages by 2025, and the demand for water is expected to have increased by 50% in 2050 (United Nations, 2018).

In addition, the impact of climate change on intensity, frequency, and duration of droughts grows from meteorological to agricultural to hydrological drought (Wang et al., 2011). Specifically, an increase in agricultural drought occurrence is predicted, whereas little change in meteorological or hydrological drought occurrences are projected (Leng et al., 2015). Additionally, as climate change is expected to increase in the 21st century, terrestrial ecosystems will take longer to recover after droughts (Schwalm et al., 2017). Moreover, a chronic state of incomplete recovery may occur in the 21st century. Multi-seasonal and multi-year recovery times may become more frequent and this trend may similarly be apparent in extreme recovery times (Schwalm et al., 2017; Trenberth et al., 2014). Moreover, global impact models underestimate the extreme nature of impacts in multi-sectors, as future extreme climate and weather events may present greater risks to society (Schewe et al., 2019). Understanding how well the impact models are sufficiently representing extreme events (such as drought) on the natural and human systems are indispensable in the future. Hence, the projected changes in drought severity and intensity in the 21st century need further investigation and management for their magnitude and coverage. Further, documentary evidence is invaluable for a better understanding of future droughts under the changing climate due to increased concentrations of greenhouse gases (Brázdil et al., 2018). Specific measures should be taken by specific sectors to better mitigate the future climate change effects associated with specific warming levels (Leng et al., 2015).

5 | DROUGHT IMPACT ON SOCIO-ENVIRONMENTAL SYSTEMS AND ITS MITIGATION

5.1 | Drought impacts on water use

Drought impacts are key to understanding societal vulnerability (Wilhite, Svoboda, & Hayes, 2007). Throughout history, many regions and territories of the world have been affected by severe drought events. Examples of some areas vulnerable to drought include the Sahelian region, the Horn of Africa, the United States, Canada, Europe, Iran, Russia, China, India, and Australia (Spinoni, Naumann, Carrao, Barbosa, & Vogt, 2014). Drought events that occurred at various points in history have led to societal and environmental catastrophes. Across the world, over one billion people were affected by droughts in the period 1995–2015 (Centre for Research on the Epidemiology of Disasters and United Nations Secretariat of the International Strategy for Disaster Reduction, 2015); meanwhile, the annual economic losses that resulted from drought reached as much as tens of billions of US dollars (Below et al., 2007).

Drought impacts the ecosystem and society in different ways, and many of the impacts are associated with living things and the environment (Van Loon & Laaha, 2015). When lack of water persists in the hydrological system, water scarcity occurs in almost all economic infrastructures, and in severe cases it could limit the supply of freshwater (Tokarczyk, 2013). Drought impacts can be witnessed in drinking water supply, irrigated agriculture, marine transportation, hydropower, industries, and recreational facilities (Sheffield et al., 2012; Stagge et al., 2015). As a result of drought, lack of access to water, reductions in agricultural production, food, and livelihoods have been observed to hinder societies (Muller, 2014). Maintaining water resources whenever available has tremendous benefits to society. Hence, monitoring and management of drought is necessary to reduce its global impacts.

Global human water use has more than doubled and affected streamflow over the past half-century (Wada, Van Beek, Wanders, & Bierkens, 2013). Moreover, human water consumption has substantially reduced local and downstream streamflow and subsequently intensified the magnitude of droughts by 10–500% (Wada et al., 2013). If the imbalance of water availability and society's demand for water exist, the impacts of drought could be severe (Sheffield et al., 2012; Tallaksen & Van Lanen, 2004). Moreover, Wada et al. (2013) indicated that human water consumption alone increased global hydrological drought frequency by 27%, irrigation being responsible for the intensification of droughts along with industrial and household consumption. Hence, accurate and timely understanding of hydrological drought is crucial to benefit global societies.

5.2 | Drought health impact

Recently, scientists have noted that droughts can often have significant health effects, typically mediated through complex environmental, economic, and social degradations (Berman et al., 2017; Vins et al., 2015). Berman et al. (2017) examined for the first time the association between drought exposure and health and found that drought severity has a significant effect on public health. Furthermore, when the drought became more severe, an increase of around 15% in suicides among working-age men was observed in Australia (Hanigan, Butler, Kokic, & Hutchinson, 2012). When comparing areas with high and low frequencies of drought, higher mortality and cardiovascular disease risks due to drought are observed under high frequencies of drought (Berman et al., 2017). In addition, increased amounts of airborne dust and particulate air pollution associated with drought can exacerbate asthma, respiratory allergies, and airway disease (Hanigan et al., 2012; Page, Morrell, & Taylor, 2002).

Rural dwellers are more sensitive to drought impacts and more likely to face distress and shock during extreme drought events (O'Brien, Berry, Coleman, & Hanigan, 2014). Droughts increase the mental stress on farmers and farming communities as a result of the unexpected loss of livestock and crops. This situation may be linked to psychological stresses and depression in humans that may lead the farmers to become dysfunctional (Berman et al., 2017). During high severity, worsening drought periods, the risk of mortality was four times greater in rural than in urban areas (Berman et al., 2017). Drought-related suicides and mental health problems were also most severe among rural populations associated with agricultural drought (Hanigan et al., 2012). For example, about 9% of total male deaths (aged 30–49) in rural Australia were because of suicides committed due to drought (Hanigan et al., 2012). Page et al. (2002) also suggested an increased risk for women during drought years, due to mental health problems linked to drought event exposure as they are more responsible for household activities. The 2003 European heatwave and drought caused a high human death toll, mainly due to circulatory- and respiratory-related problems, due to which as many as 70,000 excess deaths were estimated in Europe (Robine et al., 2008; Schewe et al., 2019). This was more pronounced among the elderly population and vulnerable societies.

However, further investigation is needed because the links between drought and disease are not fully understood, and the likely increased future global drought events could further aggravate the problem. Studies on the effects of drought on human health are mainly undertaken in developed countries such as the United States (Berman et al., 2017) and Australia (Hanigan et al., 2012; O'Brien et al., 2014). It is worth mentioning that the worst effects of drought on public health would be in the drought-vulnerable developing countries where inadequate adaptation strategies exist.

5.3 | Impacts of drought on carbon cycle

Global terrestrial carbon sequestration offsets one-third of the world's fossil fuel emissions (Wolf et al., 2016). Terrestrial ecosystems can also absorb 30% of anthropogenic carbon dioxide (CO_2) emissions (Humphrey et al., 2018). This suggests that droughts could have widespread effects on terrestrial carbon cycling at the global scale (Frank et al., 2015). Hence, highlighting the underlying concepts and complex impacts of drought on the land ecosystem carbon cycle has substantial societal benefits. Studies suggest that the response of terrestrial ecosystems to drought has been challenging in quantifying the carbon cycle (Anderegg et al., 2015; Leitold et al., 2018; Stocker et al., 2018, 2019; Yang et al., 2018). Different studies have been conducted to understand the carbon cycle feedbacks to drought events (Anderegg et al., 2015; Stocker et al., 2018; Xiao et al., 2009). In China, Xiao et al. (2009) analyzed century-scale (1901–2002) drought effects on terrestrial ecosystem carbon balance and demonstrated that severe long droughts had significant effects on terrestrial carbon cycling. Yi, Pendall, and Ciais (2015) collected evidence on how drought events disturb terrestrial carbon dynamics and demonstrated different drought impacts that vary from season to season and from biome to biome. According to Brando et al. (2019), droughts have been reducing forest carbon uptake and stocks by decreasing photosynthesis, elevating tree mortality, increasing autotrophic respiration, and promoting wildfires. These indicate that the response of forest ecosystems to drought is increasingly important in the context of a warming climate. These effects are typically observed in the Amazonia and Congo basin where forests are abundantly found (Brando et al., 2019). This plays a role in supporting the efforts towards climate change mitigation across the globe.

Drought limits plant growth and phenology, and prolonged dry periods can have far-reaching impacts on the ecosystem carbon balance and structure (Stocker et al., 2018, 2019). According to van der Molen et al. (2011), plants respond physiologically and structurally to prevent excessive water loss and may aggravate species competition during drought. In addition, when drought occurs, soils dry out and plants reduce photosynthesis and breathe less CO_2 (Humphrey et al., 2018). As a consequence, plants' ability to capture CO_2 from the atmosphere reduces. This suggests that CO_2 concentration in the atmosphere increases as drought increases. Compounded with other extreme events, the impact of drought on the terrestrial carbon sink intensifies as the terrestrial ecosystems' carbon uptake is highly sensitive to large-scale extreme climate events (Frank et al., 2015; Wolf et al., 2016). These extreme events include droughts, heatwaves, frosts, windstorms, and fires, which may impact the functioning of terrestrial ecosystems and carbon cycling (Frank et al., 2015; Sippel et al., 2018). For example, Wolf et al. (2016) investigated the extreme 2012 US summer drought when a record warm spring was followed by a dry and hot summer. This demonstrated that losses in net carbon uptake during the summer were largely offset by carbon gains in the extremely warm spring. This suggests that the warm spring reduced the carbon cycle dependence on timing (Sippel et al., 2018).

Different techniques are used to understand the impacts of droughts on the carbon cycle, including vapor pressure-deficit data, soil moisture dataset, remotely sensed greenness changes, and tree-ring analysis (Anderegg et al., 2015; Stocker et al., 2018, 2019; Xiao et al., 2009). These factors are known to strongly affect plant physiology under the context of drought events. Using these techniques, different droughts were studied in response to carbon sequestration globally. For example, the Amazon drought caused forest changes translating to millions of metric tons of annual carbon loss between the 2005 and 2008 drought years (Doughty et al., 2015; Yang et al., 2018). In-depth analysis of the response of the terrestrial carbon cycle to the 2015–2016 El Niño-imposed extreme warming and dry conditions revealed a decrease in productivity, rather than an increase in respiration in response to prolonged drought conditions (Bastos et al., 2018). This El Nino drought has increased canopy turnover in Amazon forests via reducing forest net primary productivity and increasing canopy tree mortality, thereby altering the net forest carbon balance (Leitold et al., 2018). For instance, in the Amazon severe drought suppressed photosynthesis by 0.38 petagrams of carbon in 2010. Moreover, the 2015–2016 El Nino Amazon drought conditions accelerated forests' canopy turnover and increased coarse woody debris production by 62%, suggesting carbon sources (Leitold et al., 2018). This indicates the increasing frequency of drought is changing the Amazon from a carbon sink into a source (Yang et al., 2018).

With increasing climate change, the intensity and frequency of droughts will likely increase (Brando et al., 2019; Sippel et al., 2018). As a result, forests may lose their role as a robust sink of carbon, which will exacerbate potential warming trends (Yang et al., 2018). In the Amazon, even a single season of drought can reduce CO_2 absorption ability for years to come (Yang et al., 2018). The impacts of future droughts will depend on their severity, duration, and frequency, and the compound effects along with the land cover type and forest species (Frank et al., 2015).

5.4 | Drought mitigation

Drought has multifunctional dimensions. Putting mitigation measures into practice requires comprehensive knowledge of a drought's behavior and its uncertainties. As a result, human intervention should adhere to drought mitigation. Improvements in economic, political, and agricultural policies, at local and global scales, are needed to tackle the impact of humans and climate in drought. There are different occasions where drought mitigation is critically valid. For instance, developmental works in transboundary basins alter the hydrological processes of the upstream and downstream riparian countries. Human developmental activities such as dredging, dam construction, and hydropower generation may result in severe droughts and suppress irrigation, fishing, and navigation in river basins of the downstream riparian countries (Stone, 2010). Dams may also aid in mitigating drought by controlling the flow of water seasonally and benefit downstream areas by storing water in the rainy season and releasing it during the dry season (Lu & Siew, 2006). These impacts occur across different transboundary river basins, such as the Mekong river basin in Southeast Asia. Hence, drought mitigation requires wise management and cooperation between countries and societies sharing common transboundary river basins. An entry point for drought mitigation is to build water resilience to high water demands. For a quicker drought recovery, alleviating food and water deficits should be given priority to prevent famine that may arise as a consequence of drought (Schwalm et al., 2017).

Similarly, early drought monitoring is crucial in replacing the crisis-driven approach with a long-lasting, integrated, risk-resilient approach (Muller, 2014). A holistic and coherent drought policy for reducing the risk of droughts and meeting local needs to build resiliencies is required. This would be sounder if drought-affected countries implement a policy to guide and facilitate coordination between partners and governments, from national to local levels. Protecting livelihoods from drought shocks and risks should also be a core principle, along with empowering and developing the people from future drought cycles. It is important to target regular drought-prone areas and potential development zones for coping and adapting to the drought. This will help to direct efforts towards coordinated works between the respective agents in reducing drought-induced risks and vulnerabilities, and significantly weakening adverse drought events and shocks. It is also believed that the public health problems associated with drought events should also receive great attention in the efforts towards drought monitoring and management capabilities. More studies are needed to explore different strategies to address potential droughts in the future.

Drought impact alleviation depends on mitigating and coping with droughts. Designing active responses to droughts is more important than reactive, and the active responses should be based on risk management, rather than crisis management (Sivakumar et al., 2014; Tadesse, Haile, Senay, Wardlow, & Knutson, 2008). Drought mitigation is useful for effective drought monitoring systems and management and needs to move from a reactive approach to a proactive approach (Rossi, 2000).

Drought mitigation depends on understanding how hydro-meteorological variabilities in water resource systems relate, and how the information derived from individual drought parameters is utilized for drought mitigation (Pozzi et al., 2013). In addition, drought predictions using different data sources such as from in situ or satellite products are vital for society via drought mitigation. For instance, the use of hydrological models enables satellite data to be used for drought forecasting (Mwangi, Wetterhall, Dutra, Di Giuseppe, & Pappenberger, 2014; Sheffield et al., 2014), and this is important for earlier drought warnings (Funk, 2009). Additionally, remote sensing satellite products used for drought forecasting support humanitarian aid organizations (Anderson et al., 2012; Shukla, McNally, Husak, & Funk, 2014). Hence, for efficient drought mitigation measures, relevant policies for drought mitigation are important.

5.5 | Drought recovery

Drought recovery generally focuses on precipitation that ends the drought by alleviating the water deficit for effective ecosystem functioning (Banerjee, Bark, Connor, & Crossman, 2013; DeChant & Moradkhani, 2015; Pan, Yuan, & Wood, 2013). When an ecosystem returns to its pre-drought level, one would say that drought recovery has occurred. Drought recovery is a function of the initial drought intensity, recovery time (the time at which the drought area is expected to recover), and recovery rate (the speed at which the region rebounds from drought) (DeChant & Moradkhani, 2015; Schwalm et al., 2017).

Drought recovery time indicates how long an ecosystem requires to revert to its pre-drought functional state (Schwalm et al., 2017). It is tracked starting from the first post-drought month for a region under drought. Recovery time is critical for ecosystem functions and resilience (Banerjee et al., 2013; DeChant & Moradkhani, 2015). Hence, across diverse ecosystems, drought recovery times are strongly associated with climate, carbon cycle dynamics, biodiversity, and CO_2 fertilization (Schwalm et al., 2017). However, drought recovery time has become a subject of contradictory conclusions recently. Schwalm et al. (2017) have reported the drought recovery time to be the longest in the tropics and high northern latitudes suggesting it could last for more than 12 months to recover to its pre-drought condition. Thus, Schwalm et al. (2017) have concluded that spatiotemporal patterns of drought recovery are evident linked to spatial gradients in productive potential. On the contrary, Yu et al. (2017) found an opposing pattern suggesting the drought recovery time is shortest in the tropics and high northern latitudes lasting for less than 4 months to recover to its pre-drought condition. Following this controversy, a revisiting assessment on the drought recovery time was made by Liu et al. (2019) to understand the underlying reasons. Liu et al. (2019) found that the study time frame employed, methods used for drought identification, the definitions used in detecting the recovery level and consideration of non-impactful droughts (droughts that did not show ecosystem production reduction) are main contributing factors that lead to a strong bias in understanding the drought recovery time. Furthermore, Liu et al. (2019) indicated that the drought recovery time is longest in some tropical regions but not in high northern latitudes.

Additionally, drought recovery depends on the rate at which deficits from the initial conditions are reduced/minimized. Recovery rate indicates the speed at which a specific drought event returns to its normal conditions. The rate of drought recovery appears to be more related to the specific drought-affected location than drought intensity. The initial drought intensity is related to drought events and the severity of their impact over a specific region. Similarly, drought recovery time is directly related to drought intensity; that is, as intensity increases recovery time increases (DeChant &

Moradkhani, 2015). Generally, longer and more severe droughts are associated with longer recovery times (Schwalm et al., 2017).

Drought recovery also depends on plant ability to respond to drought. According to Anderegg et al. (2015), during post-drought events forests are less able to act as a sink for carbon as they exhibit a drought "legacy effect" with 1–4 years of reduced growth. In addition, ecosystem responses can exceed the duration of the climate impacts, as delayed effects on the carbon cycle persist due to drought (Frank et al., 2015). For instance, a post-drought decline in carbon sinking ability is observed in Amazonia (Yang et al., 2018) due to the shifting of carbon from the roots towards the canopy (Doughty et al., 2015). Hence, incorporating forest legacy effects into climate–carbon cycle models are important for capturing the effects of drought in carbon cycling (Anderegg et al., 2015; van der Molen et al., 2011). Furthermore, in the human-modified world, the increased influence of anthropogenic activities is affecting drought termination phases (Margariti et al., 2019). Human activities including water abstractions, reservoirs, and water transfers are affecting the duration, rate, and recovery time of drought events (Margariti et al., 2019; Schwalm et al., 2017). Hence, drought recovery forecasting is important for improving drought management decisions in the Anthropocene.

For assessing drought recovery, a probabilistic framework developed by Pan et al. (2013) was helpful in identifying the cumulative precipitation needed for recovery and its associated uncertainties. The recovery process is controlled by several factors, such as the initial moisture condition, the amount and timing of precipitation, and the temperature (DeChant & Moradkhani, 2015; Pan et al., 2013). As a result, drought recovery forecasts (recovery time and rate) are highly sensitive to initial conditions. Knowing how much cumulative precipitation is most likely needed for a region in drought to recover is by far the most vital information during drought forecasts. However, the temporal variability of precipitation and other initial factors can result in significant uncertainty during drought forecasting. This uncertainty is associated with drought recovery for different locations, recovery times, and captures using conditional probabilities via a joint distribution model (Pan et al., 2013).

6 | CONCLUSION

Drought is the furthest-reaching of all-natural disasters on Earth in hindering societies and the environment. In the human-modified world, scientific understanding of drought has continuously increased with recent global developments regarding recurrent drought events. This review provides an overview of the various characteristics of drought from different perspectives, focusing on progress in recent years. The various definitions and concepts of drought, and the drought types categorized on the basis of various drought indicators, including the newly developed, are reviewed and highlighted. A number of drought indices and indicators, characterization and forecasting, drought recovery, impacts, and recovery are presented.

The intensity, severity, duration, and geographic extent of drought are likely to increase in the 21st century (Seneviratne et al., 2012). The tendency shows that currently non-drought geographical areas will face more frequent exposure, leading to a greater risk of adverse drought-related problems to the vulnerable people. These drought impacts include public health problems as a consequence of drought (Berman et al., 2017). An in-depth investigation of direct and indirect drought impacts is needed to capture the drought effects from different dimensions. This would be important for policymakers and implementers when designing plans for drought forecasting, preparedness, and early warning.

Drought is a slowly developing phenomenon over a long duration, and its root cause is still not fully understood; whether it is periodic in nature, due to the impact of climate change, or due to growing water demand is far from conclusive. Moreover, the real effect of climate change on drought occurrence has not been well investigated regionally or globally. Extended efforts are needed in investigating and forecasting possible drought events in the future. Hence, focusing on drought hydrology is believed to offer solutions to drought-vulnerable people worldwide. Drought forecasting, early warning, mitigations, resilience, and recovery should be at the forefront of consideration in drought hydrology studies and implementations. This could bring environmental and societal changes as a result of drought monitoring and alleviation. Future research may benefit from the use of a more holistic framework to systematically investigate how combinations of and interactions between various factors influence drought.

ACKNOWLEDGMENTS

The first author is sponsored by the Chinese Academy of Sciences (CAS)-the World Academy of Sciences (TWAS) President's Fellowship Program for his PhD study at the University of Chinese Academy of Sciences.

CONFLICT OF INTEREST

The authors have declared no conflicts of interest for this article.

AUTHOR CONTRIBUTIONS

Gebremedhin Gebremeskel Haile: Conceptualization; methodology; writing-original draft. **Qiuhong Tang**: Conceptualization; funding acquisition; methodology; supervision. **Wenhong Li**: Methodology; supervision; writing-review and editing. **Xingcai Liu**: Writing-review and editing. **Xuejun Zhang**: Writing-review and editing.

ORCID

Gebremedhin Gebremeskel Haile https://orcid.org/0000-0003-2807-5330
Qiuhong Tang https://orcid.org/0000-0002-0886-6699
Wenhong Li https://orcid.org/0000-0002-5990-2004
Xingcai Liu https://orcid.org/0000-0001-5726-7353
Xuejun Zhang https://orcid.org/0000-0002-2152-5418

FURTHER READING

Gibbs, W. J. (1967). *Rainfall deciles as drought indicators Bureau of Meteorology, Bulletin 48*. Melbourne, Australia: Commonwealth of Australia.

Guha-Sapir, D., Hargitt, D., & Hoyois, P. (2004). *Thirty years of natural disasters 1974–2003: The numbers*. Leuven, Belgium: Presses Universitaires de Louvain.

Lenton, T. M., Held, H., Kriegler, E., Hall, J. W., Lucht, W., Rahmstorf, S., & Schellnhuber, H. J. (2008). Tipping elements in the Earth's climate system. *Proceedings of the National Academy of Sciences*, *105*(6), 1786–1793.

Rojas, O., Vrieling, A., & Rembold, F. (2011). Assessing drought probability for agricultural areas in Africa with coarse resolution remote sensing imagery. *Remote Sensing of Environment*, *115*(2), 343–352.

Shafer, B. A. (1982). Development of a surface water supply index (SWSI) to assess the severity of drought conditions in snowpack runoff areas. In *Proceedings of the 50th Annual Western Snow Conference* (pp. 164–175). Fort Collins, CO: Colorado State University.

Wilhite, D. A. (2016). *Droughts: A global assesment Routledge Hazards and Disasters Series* (Vol. I–II). London, England: Routledge.

Wilhite, D. A., & Glantz, M. H. (1985). Understanding: The drought phenomenon: The role of definitions. *Water International*, *10*(3), 111–120.

Yang, W., Seager, R., Cane, M. A., & Lyon, B. (2014). The East African long rains in observations and models. *Journal of Climate*, *27*(19), 7185–7202.

REFERENCES

AghaKouchak, A. (2015). A multivariate approach for persistence-based drought prediction: Application to the 2010–2011 East Africa drought. *Journal of Hydrology*, *526*, 127–135.

AghaKouchak, A., Farahmand, A., Melton, F. S., Teixeira, J., Anderson, M. C., Wardlow, B. D., & Hain, C. R. (2015). Remote sensing of drought: Progress, challenges and opportunities. *Reviews of Geophysics*, *53*(2), 452–480.

AghaKouchak, A., Feldman, D., Hoerling, M., Huxman, T., & Lund, J. (2015). Water and climate: Recognize anthropogenic drought. *Nature News*, *524*(7566), 409–411.

Anderegg, W. R., Schwalm, C., Biondi, F., Camarero, J. J., Koch, G., Litvak, M., … Wolf, A. (2015). Pervasive drought legacies in forest ecosystems and their implications for carbon cycle models. *Science*, *349*(6247), 528–532.

Anderson, W. B., Zaitchik, B. F., Hain, C. R., Anderson, M. C., Yilmaz, M. T., Mecikalski, J., & Schultz, L. (2012). Towards an integrated soil moisture drought monitor for East Africa. *Hydrology and Earth System Sciences*, *16*(8), 2893–2913.

Bachmair, S., Stahl, K., Collins, K., Hannaford, J., Acreman, M., Svoboda, M., … Crossman, N. D. (2016). Drought indicators revisited: The need for a wider consideration of environment and society. *WIREs Water*, *3*(4), 516–536.

Banerjee, O., Bark, R., Connor, J., & Crossman, N. D. (2013). An ecosystem services approach to estimating economic losses associated with drought. *Ecological Economics*, *91*, 19–27.

Bastos, A., Friedlingstein, P., Sitch, S., Chen, C., Mialon, A., Wigneron, J. P., … Chevallier, F. (2018). Impact of the 2015/2016 El Niño on the terrestrial carbon cycle constrained by bottom-up and top-down approaches. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *373*(1760), 20170304.

Below, R., Grover-Kopec, E., & Dilley, M. (2007). Documenting drought-related disasters: A global reassessment. *The Journal of Environment & Development*, *16*(3), 328–344.

Benson, C., & Clay, E. (1998). The impact of drought on sub-Saharan African economies: A preliminary examination. World Bank Technical Paper No. WTP 401, 80 pp. Washington, DC: The World Bank.

Bergman, K. H., Ropelewski, C. F., & Halpert, M. S. (1986). The record southeast drought of 1986. *Weatherwise*, *39*(5), 262–266.

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. *The Lancet Planetary Health*, *1*(1), e17–e25.

Bond, N. R., Lake, P. S., & Arthington, A. H. (2008). The impacts of drought on freshwater ecosystems: An Australian perspective. *Hydrobiologia*, *600*(1), 3–16.

Brando, P. M., Paolucci, L., Ummenhofer, C. C., Ordway, E. M., Hartmann, H., Cattau, M. E., … Balch, J. (2019). Droughts, wildfires, and forest carbon cycling: A pantropical synthesis. *Annual Review of Earth and Planetary Sciences*, *47*, 555–581.

Brázdil, R., Kiss, A., Luterbacher, J., Nash, D. J., & Řezníčková, L. (2018). Documentary data and the study of past droughts: A global state of the art. *Climate of the Past*, *14*(12), 1915–1960.

Burke, E. J., Brown, S. J., & Christidis, N. (2006). Modeling the recent evolution of global drought and projections for the twenty-first century with the Hadley Centre climate model. *Journal of Hydrometeorology*, *7*(5), 1113–1125.

Calow, R. C., MacDonald, A. M., Nicol, A. L., & Robins, N. S. (2010). Ground water security and drought in Africa: Linking availability, access, and demand. *Groundwater*, *48*(2), 246–256.

Centre for Research on the Epidemiology of Disasters and United Nations Secretariat of the International Strategy for Disaster Reduction. (2015). The human cost of weather-related disasters: 1995–2015. Retrieved from http://www.unisdr.org/2015/docs/climatechange/COP21_WeatherDisastersReport_2015_FINAL.pdf

Chen, L. G., Gottschalck, J., Hartman, A., Miskus, D., Tinker, R., & Artusa, A. (2019). Flash drought characteristics based on US drought monitor. *Atmosphere*, *10*(9), 498.

Crausbay, S. D., Ramirez, A. R., Carter, S. L., Cross, M. S., Hall, K. R., Bathke, D. J., … Dunham, J. B. (2017). Defining ecological drought for the twenty-first century. *Bulletin of the American Meteorological Society*, *98*(12), 2543–2550.

Cumani, M., & Rojas, O. (2016). *Characterization of the agricultural drought prone areas on a global scale*. Rome, Italy: FAO.

Dai, A. (2011). Drought under global warming: A review. *WIREs Climate Change*, *2*(1), 45–65.

DeChant, C. M., & Moradkhani, H. (2015). Analyzing the sensitivity of drought recovery forecasts to land surface initial conditions. *Journal of Hydrology*, *526*, 89–100.

Demetillo, M. A. G., Anderson, J. F., Geddes, J. A., Yang, X., Najacht, E. Y., Herrera, S. A., … Pusede, S. E. (2019). Observing severe drought influences on ozone air pollution in California. *Environmental Science & Technology*, *53*(9), 4695–4706.

Diffenbaugh, N. S., Swain, D. L., & Touma, D. (2015). Anthropogenic warming has increased drought risk in California. *Proceedings of the National Academy of Sciences*, *112*(13), 3931–3936.

Doughty, C. E., Metcalfe, D. B., Girardin, C. A. J., Amézquita, F. F., Cabrera, D. G., Huasco, W. H., … Feldpausch, T. R. (2015). Drought impact on forest carbon dynamics and fluxes in Amazonia. *Nature*, *519*(7541), 78–82.

Eltahir, E. A., & Yeh, P. J. F. (1999). On the asymmetric response of aquifer water level to floods and droughts in Illinois. *Water Resources Research*, *35*(4), 1199–1217.

Esfahanian, E., Nejadhashemi, A. P., Abouali, M., Adhikari, U., Zhang, Z., Daneshvar, F., & Herman, M. R. (2017). Development and evaluation of a comprehensive drought index. *Journal of Environmental Management*, *185*, 31–43.

Esfahanian, E., Nejadhashemi, A. P., Abouali, M., Daneshvar, F., Alireza, A. R., Herman, M. R., & Tang, Y. (2016). Defining drought in the context of stream health. *Ecological Engineering*, *94*, 668–681.

Fleig, A. K., Tallaksen, L. M., Hisdal, H., & Demuth, S. (2006). A global evaluation of streamflow drought characteristics. *Hydrology and Earth System Sciences Discussions*, *10*(4), 535–552.

Ford, T. W., McRoberts, D. B., Quiring, S. M., & Hall, R. E. (2015). On the utility of *in situ* soil moisture observations for flash drought early warning in Oklahoma, USA. *Geophysical Research Letters*, *42*(22), 9790–9798.

Frank, D., Reichstein, M., Bahn, M., Thonicke, K., Frank, D., Mahecha, M. D., … Beer, C. (2015). Effects of climate extremes on the terrestrial carbon cycle: Concepts, processes and potential future impacts. *Global Change Biology*, *21*(8), 2861–2880.

Funk, C. (2009). New satellite observations and rainfall forecasts help provide earlier warning of African drought. *The Earth Observer*, *21*(1), 23–27.

Gocic, M., & Trajkovic, S. (2014). Spatiotemporal characteristics of drought in Serbia. *Journal of Hydrology*, *510*, 110–123.

Gommes, R., & Petrassi, F. (1994). *Rainfall variability and drought in sub-Saharan Africa since 1960. Agro-meteorology series* (Working Paper No. 9). Rome, Italy: FAO.

Grayson, R., & Bloschl, G. (Eds.). (2001). *Spatial patterns in catchment hydrology: Observations and modelling*. Cambridge, England: Cambridge University Press.

Gudmundsson, L., Seneviratne, S. I., & Zhang, X. (2017). Anthropogenic climate change detected in European renewable freshwater resources. *Nature Climate Change*, *7*(11), 813–816.

Haddeland, I., Clark, D. B., Franssen, W., Ludwig, F., Voß, F., Arnell, N. W., … Gomes, S. (2011). Multimodel estimate of the global terrestrial water balance: Setup and first results. *Journal of Hydrometeorology*, *12*(5), 869–884.

Haile, G. G., Tang, Q., Sun, S., Huang, Z., Zhang, X., & Liu, X. (2019). Droughts in East Africa: Causes, impacts and resilience. *Earth-Science Reviews*, *193*, 146–161.

Hanigan, I. C., Butler, C. D., Kokic, P. N., & Hutchinson, M. F. (2012). Suicide and drought in New South Wales, Australia, 1970–2007. *Proceedings of the National Academy of Sciences*, *109*(35), 13950–13955.

Hao, Z., & AghaKouchak, A. (2014). A nonparametric multivariate multi-index drought monitoring framework. *Journal of Hydrometeorology*, *15*(1), 89–101.

Hao, Z., & Singh, V. P. (2015). Drought characterization from a multivariate perspective: A review. *Journal of Hydrology*, *527*, 668–678.

Hao, Z., Singh, V. P., & Xia, Y. (2018). Seasonal drought prediction: Advances, challenges, and future prospects. *Reviews of Geophysics*, *56*(1), 108–141.

Hartmann, D. L., Tank, A. M. K., Rusticucci, M., Alexander, L. V., Brönnimann, S., Charabi, Y. A. R., … Soden, B. J. (2013). Observations: Atmosphere and surface. In *Climate change 2013 the physical science basis: Working Group I contribution to the fifth assessment report of the Intergovernmental Panel on Climate Change*. Cambridge, England/New York, NY: Cambridge University Press.

Hayes, M., Svoboda, M., Wall, N., & Widhalm, M. (2011). The Lincoln declaration on drought indices: Universal meteorological drought index recommended. *Bulletin of the American Meteorological Society*, *92*(4), 485–488.

Hayes, M. J., Svoboda, M. D., Wardlow, B. D., Anderson, M. C., & Kogan, F. (2012). Drought monitoring: Historical and current perspectives. In *Remote sensing of drought: Innovative monitoring approaches* (pp. 1–19). Boca Raton, FL: CRC Press.

Heim, R. R., Jr. (2002). A review of twentieth-century drought indices used in the United States. *Bulletin of the American Meteorological Society*, *83*(8), 1149–1166.

Herrera-Estrada, J. E., Satoh, Y., & Sheffield, J. (2017). Spatiotemporal dynamics of global drought. *Geophysical Research Letters*, *44*(5), 2254–2263.

Hollinger, S. E., Isard, S. A., & Welford, M. R. (1993). A new soil moisture drought index for predicting crop yields. *Proceedings of the Eighth Conference on Applied Climatology* (pp. 187–190). Anaheim, CA: American Meteorological Society.

Hollmann, R., Merchant, C. J., Saunders, R., Downy, C., Buchwitz, M., Cazenave, A., … Holzer-Popp, T. (2013). The ESA climate change initiative: Satellite data records for essential climate variables. *Bulletin of the American Meteorological Society*, *94*(10), 1541–1552.

Huang, S., Li, P., Huang, Q., Leng, G., Hou, B., & Ma, L. (2017). The propagation from meteorological to hydrological drought and its potential influence factors. *Journal of Hydrology*, *547*, 184–195.

Humphrey, V., Zscheischler, J., Ciais, P., Gudmundsson, L., Sitch, S., & Seneviratne, S. I. (2018). Sensitivity of atmospheric CO_2 growth rate to observed changes in terrestrial water storage. *Nature*, *560*(7720), 628–631.

Intergovernmental Panel on Climate Change (2007). Climate change 2007: The physical science basis. In S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, et al. (Eds.), *Contribution of Working Group I to the fourth assessment report of the Intergovernmental Panel on Climate Change* (p. 996). Cambridge, England/New York, NY: Cambridge University Press.

Jaeger, W. K., Amos, A., Conklin, D. R., Langpap, C., Moore, K., & Plantinga, A. J. (2019). Scope and limitations of drought management within complex human–natural systems. *Nature Sustainability*, *2*(8), 710–717.

Kao, S. C., & Govindaraju, R. S. (2010). A copula-based joint deficit index for droughts. *Journal of Hydrology*, *380*(1–2), 121–134.

Karl, T. R., & Young, P. J. (1987). The 1986 southeast drought in historical perspective. *Bulletin of the American Meteorological Society*, *68*(7), 773–778.

Kassas, M. (1987). Drought and desertification. *Land Use Policy*, *4*(4), 389–400.

Kéfi, S., Rietkerk, M., Alados, C. L., Pueyo, Y., Papanastasis, V. P., Elaich, A., & De Ruiter, P. C. (2007). Spatial vegetation patterns and imminent desertification in Mediterranean arid ecosystems. *Nature*, *449*(7159), 213–217.

Kerr, Y. H., Waldteufel, P., Wigneron, J. P., Martinuzzi, J. A. M. J., Font, J., & Berger, M. (2001). Soil moisture retrieval from space: The Soil Moisture and Ocean Salinity (SMOS) mission. *IEEE Transactions on Geoscience and Remote Sensing*, *39*(8), 1729–1735.

Keyantash, J., & Dracup, J. A. (2002). The quantification of drought: An evaluation of drought indices. *Bulletin of the American Meteorological Society*, *83*(8), 1167–1180.

Kim, E. S. (2010). Simulation of daily soil moisture content and reconstruction of drought events from the early 20th century in Seoul, Korea, using a Hydrological Simulation Model, BROOK. *Journal of Ecology and Environment*, *33*(1), 47–57.

Leitold, V., Morton, D. C., Longo, M., dos-Santos, M. N., Keller, M., & Scaranello, M. (2018). El Niño drought increased canopy turnover in Amazon forests. *New Phytologist*, *219*(3), 959–971.

Leng, G., Tang, Q., & Rayburg, S. (2015). Climate change impacts on meteorological, agricultural and hydrological droughts in China. *Global and Planetary Change*, *126*, 23–34.

Liu, L., Gudmundsson, L., Hauser, M., Qin, D., Li, S., & Seneviratne, S. I. (2019). Revisiting assessments of ecosystem drought recovery. *Environmental Research Letters*, *14*, 1–10. https://doi.org/10.1088/1748-9326/ab4c61

Liu, W. T., & Kogan, F. N. (1996). Monitoring regional drought using the vegetation condition index. *International Journal of Remote Sensing*, *17*(14), 2761–2782.

Lloyd-Hughes, B. (2014). The impracticality of a universal drought definition. *Theoretical and Applied Climatology*, *117*(3–4), 607–611.

Lu, X. X., & Siew, R. Y. (2006). Water discharge and sediment flux changes over the past decades in the lower Mekong River: Possible impacts of the Chinese dams. *Hydrology and Earth System Sciences Discussions*, *10*(2), 181–195.

Lyon, B., Bell, M. A., Tippett, M. K., Kumar, A., Hoerling, M. P., Quan, X. W., & Wang, H. (2012). Baseline probabilities for the seasonal prediction of meteorological drought. *Journal of Applied Meteorology and Climatology*, *51*(7), 1222–1237.

Mao, Y., Wu, Z., He, H., Lu, G., Xu, H., & Lin, Q. (2017). Spatio-temporal analysis of drought in a typical plain region based on the soil moisture anomaly percentage index. *Science of the Total Environment*, *576*, 752–765.

Margariti, J., Rangecroft, S., Parry, S., Wendt, D. E., & Van Loon, A. F. (2019). Anthropogenic activities alter drought termination. *Elementa: Science of the Anthropocene*, *7*, 27.

Marvel, K., Cook, B. I., Bonfils, C. J. W., Durack, P. J., Smerdon, J. E., & Williams, A. P. (2019). Twentieth-century hydroclimate changes consistent with human influence. *Nature*, *569*(7754), 59–65.

Masih, I., Maskey, S., Mussá, F. E. F., & Trambauer, P. (2014). A review of droughts on the African continent: A geospatial and long-term perspective. *Hydrology and Earth System Sciences*, *18*(9), 3635–3649.

McKee, T. B., Doesken, N. J., & Kleist, J. (1993). The relationship of drought frequency and duration to time scales. *Proceedings of the Eighth Conference on Applied Climatology* (Vol. 17, No. 22, pp. 179–183). Boston, MA: American Meteorological Society.

Meyer, S. J., & Hubbard, K. G. (1995). Extending the crop-specific drought index to soybean. *Proceedings of the Ninth Conference on Applied Climatology* (pp. 258–259). Dallas, TX: American Meteorological Society.

Mishra, A. K., & Singh, V. P. (2010). A review of drought concepts. *Journal of Hydrology*, *391*(12), 202–216.

Mishra, A. K., & Singh, V. P. (2011). Drought modeling—A review. *Journal of Hydrology*, *403*(12), 157–175.

Mo, K. C., & Lettenmaier, D. P. (2015). Heat wave flash droughts in decline. *Geophysical Research Letters*, *42*(8), 2823–2829.

Mo, K. C., & Lettenmaier, D. P. (2016). Precipitation deficit flash droughts over the United States. *Journal of Hydrometeorology*, *17*(4), 1169–1184.

Mo, K. C., & Lyon, B. (2015). Global meteorological drought prediction using the North American multi-model ensemble. *Journal of Hydrometeorology*, *16*(3), 1409–1424.

Moorhead, J. E., Gowda, P. H., Singh, V. P., Porter, D. O., Marek, T. H., Howell, T. A., & Stewart, B. A. (2015). Identifying and evaluating a suitable index for agricultural drought monitoring in the Texas high plains. *Journal of the American Water Resources Association*, *51*(3), 807–820.

Morid, S., Smakhtin, V., & Moghaddasi, M. (2006). Comparison of seven meteorological indices for drought monitoring in Iran. *International Journal of Climatology*, *26*(7), 971–985.

Mukherjee, S., Mishra, A., & Trenberth, K. E. (2018). Climate change and drought: A perspective on drought indices. *Current Climate Change Reports*, *4*, 145–163.

Muller, J. C. Y. (2014). Adapting to climate change and addressing drought–learning from the Red Cross Red Crescent experiences in the Horn of Africa. *Weather and Climate Extremes*, *3*, 31–36.

Mwangi, E., Wetterhall, F., Dutra, E., Di Giuseppe, F., & Pappenberger, F. (2014). Forecasting droughts in East Africa. *Hydrology and Earth System Sciences*, *18*(2), 611–620.

Nicholson, S. E. (2014). A detailed look at the recent drought situation in the Greater Horn of Africa. *Journal of Arid Environments*, *103*, 71–79.

Niemeyer, S. (2008). New drought indices. *Options Méditerranéennes Série A: Séminaires Méditerranéens*, *80*, 267–274.

NISDR (International Strategy for Disaster Reduction). (2009). *Drought risk reduction framework and practices: Contributing to the implementation of the Hyogo framework for action* (p. 213). Geneva, Switzerland: United Nations Secretariat of the International Strategy for Disaster Reduction (UNISDR).

O'Brien, L. V., Berry, H. L., Coleman, C., & Hanigan, I. C. (2014). Drought as a mental health exposure. *Environmental Research*, *131*, 181–187.

Otkin, J. A., Svoboda, M., Hunt, E. D., Ford, T. W., Anderson, M. C., Hain, C., & Basara, J. B. (2018). Flash droughts: A review and assessment of the challenges imposed by rapid-onset droughts in the United States. *Bulletin of the American Meteorological Society*, *99*(5), 911–919.

Page, A., Morrell, S., & Taylor, R. (2002). Suicide and political regime in New South Wales and Australia during the 20th century. *Journal of Epidemiology & Community Health*, *56*(10), 766–772.

Palmer, W. C. (1965). Meteorological drought, Research Paper No. 45, p. 58. Washington, DC: US Weather Bureau.

Palmer, W. C. (1968). Keeping track of crop moisture conditions, nationwide: The new crop moisture index. *Weatherwise*, *21*, 156–161.

Pan, M., Yuan, X., & Wood, E. F. (2013). A probabilistic framework for assessing drought recovery. *Geophysical Research Letters*, *40*(14), 3637–3642.

Pekel, J. F., Cottam, A., Gorelick, N., & Belward, A. S. (2016). High-resolution mapping of global surface water and its long-term changes. *Nature*, *540*(7633), 418–422.

Pozzi, W., Sheffield, J., Stefanski, R., Cripe, D., Pulwarty, R., Vogt, J. V., … Van Dijk, A. I. (2013). Toward global drought early warning capability: Expanding international cooperation for the development of a framework for monitoring and forecasting. *Bulletin of the American Meteorological Society*, *94*(6), 776–785.

Robine, J. M., Cheung, S. L. K., Le Roy, S., Van Oyen, H., Griffiths, C., Michel, J. P., & Herrmann, F. R. (2008). Death toll exceeded 70,000 in Europe during the summer of 2003. *Comptes Rendus Biologies*, *331*(2), 171–178.

Rossi, G. (2000). Drought mitigation measures: A comprehensive framework. In *Drought and drought mitigation in Europe* (pp. 233–246). Dordrecht, Netherlands: Springer.

Samaniego, L., Thober, S., Kumar, R., Wanders, N., Rakovec, O., Pan, M., … Marx, A. (2018). Anthropogenic warming exacerbates European soil moisture droughts. *Nature Climate Change*, *8*(5), 421–426.

Scaini, A., Sánchez, N., Vicente-Serrano, S. M., & Martínez-Fernández, J. (2015). SMOS-derived soil moisture anomalies and drought indices: A comparative analysis using in situ measurements. *Hydrological Processes*, *29*(3), 373–383.

Schewe, J., Gosling, S. N., Reyer, C., Zhao, F., Ciais, P., Elliott, J., … van Vliet, M. T. (2019). State-of-the-art global models underestimate impacts from climate extremes. *Nature Communications*, *10*(1), 1005.

Schwalm, C. R., Anderegg, W. R., Michalak, A. M., Fisher, J. B., Biondi, F., Koch, G., … Huntzinger, D. N. (2017). Global patterns of drought recovery. *Nature*, *548*(7666), 202–205.

Seneviratne, S. I., Nicholls, N., Easterling, D., Goodess, C. M., Kanae, S., Kossin, J., … Reichstein, M. (2012). Changes in climate extremes and their impacts on the natural physical environment. In C. B. Field, V. Barros, T. F. Stocker, D. Qin, D. J. Dokken, K. L. Ebi, et al. (Eds.), *Managing the risks of extreme events and disasters to advance climate change adaptation. A special report of Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC)* (Vol. 14, p. 12566). Cambridge, England/New York, NY: Cambridge University Press.

Sheffield, J., Andreadis, K. M., Wood, E. F., & Lettenmaier, D. P. (2009). Global and continental drought in the second half of the twentieth century: Severity–area–duration analysis and temporal variability of large-scale events. *Journal of Climate*, *22*(8), 1962–1981.

Sheffield, J., & Wood, E. F. (2008a). Global trends and variability in soil moisture and drought characteristics, 1950–2000, from observation-driven simulations of the terrestrial hydrologic cycle. *Journal of Climate*, *21*(3), 432–458.

Sheffield, J., & Wood, E. F. (2008b). Projected changes in drought occurrence under future global warming from multi-model, multi-scenario, IPCC AR4 simulations. *Climate Dynamics*, *31*(1), 79–105.

Sheffield, J., & Wood, E. F. (2012). *Drought: Past problems and future scenarios*. Milton Park, Abingdon: Routledge.

Sheffield, J., Wood, E. F., Chaney, N., Guan, K., Sadri, S., Yuan, X., … Ogallo, L. (2014). A drought monitoring and forecasting system for sub-Sahara African water resources and food security. *Bulletin of the American Meteorological Society*, *95*(6), 861–882.

Sheffield, J., Wood, E. F., & Roderick, M. L. (2012). Little change in global drought over the past 60 years. *Nature*, *491*(7424), 435–438.

Shi, H., Chen, J., Wang, K., & Niu, J. (2018). A new method and a new index for identifying socioeconomic drought events under climate change: A case study of the East River basin in China. *Science of the Total Environment*, *616*, 363–375.

Shukla, S., McNally, A., Husak, G., & Funk, C. (2014). A seasonal agricultural drought forecast system for food-insecure regions of East Africa. *Hydrology and Earth System Sciences*, *18*(10), 3907–3921.

Sippel, S., Reichstein, M., Ma, X., Mahecha, M. D., Lange, H., Flach, M., & Frank, D. (2018). Drought, heat, and the carbon cycle: A review. *Current Climate Change Reports*, *4*(3), 266–286.

Sivakumar, M. V., Stefanski, R., Bazza, M., Zelaya, S., Wilhite, D., & Magalhaes, A. R. (2014). High level meeting on national drought policy: Summary and major outcomes. *Weather and Climate Extremes*, *3*, 126–132.

Smoyer-Tomic, K. E., Klaver, J. D., Soskolne, C. L., & Spady, D. W. (2004). Health consequences of drought on the Canadian prairies. *Eco-Health*, *1*(2), SU144–SU154.

Solh, M., & van Ginkel, M. (2014). Drought preparedness and drought mitigation in the developing world′s drylands. *Weather and Climate Extremes*, *3*, 62–66.

Spinoni, J., Naumann, G., Carrao, H., Barbosa, P., & Vogt, J. (2014). World drought frequency, duration, and severity for 1951–2010. *International Journal of Climatology*, *34*(8), 2792–2804.

Stagge, J. H., Kohn, I., Tallaksen, L. M., & Stahl, K. (2015). Modeling drought impact occurrence based on meteorological drought indices in Europe. *Journal of Hydrology*, *530*, 37–50.

Steiger, N. J., Smerdon, J. E., Cook, B. I., Seager, R., Williams, A. P., & Cook, E. R. (2019). Oceanic and radiative forcing of medieval mega-droughts in the American southwest. *Science Advances*, *5*(7), eaax0087.

Steinemann, A., Hayes, M., & Cavalcanti, L. (2005). Drought indicators and triggers. In D. A. Wilhite (Ed.), *Drought and water crises: Science, technology, and management issues* (pp. 71–92). New York, NY: Marcel Dekker.

Stocker, B. D., Zscheischler, J., Keenan, T. F., Prentice, I. C., Peñuelas, J., & Seneviratne, S. I. (2018). Quantifying soil moisture impacts on light use efficiency across biomes. *New Phytologist*, *218*, 1430–1449.

Stocker, B. D., Zscheischler, J., Keenan, T. F., Prentice, I. C., Seneviratne, S. I., & Peñuelas, J. (2019). Drought impacts on terrestrial primary production underestimated by satellite monitoring. *Nature Geoscience*, *12*(4), 264–270.

Stone, R. (2010). Severe drought puts spotlight on Chinese dams. *Nature*, *327*(12), 1311.

Tadesse, T., Haile, M., Senay, G., Wardlow, B. D., & Knutson, C. L. (2008). The need for integration of drought monitoring tools for proactive food security management in sub-Saharan Africa. *Natural Resources Forum*, *32*(4), 265–279.

Tallaksen, L. M., & Van Lanen, H. A. (Eds.). (2004). *Hydrological drought: Processes and estimation methods for streamflow and groundwater Developments in water science 48* (p. 579). Amsterdam, Netherlands: Elsevier.

Tang, Q., Gao, H., Lu, H., & Lettenmaier, D. P. (2009). Remote sensing: hydrology. *Progress in Physical Geography*, *33*(4), 490–509.

Tang, Q., Zhang, X., Duan, Q., Huang, S., Yuan, X., Cui, H., … Liu, X. (2016). Hydrological monitoring and seasonal forecasting: Progress and perspectives. *Journal of Geographical Sciences*, *26*(7), 904–920.

Tokarczyk, T. (2013). Classification of low flow and hydrological drought for a river basin. *Acta Geophysica*, *61*(2), 404–421.

Touma, D., Ashfaq, M., Nayak, M. A., Kao, S. C., & Diffenbaugh, N. S. (2015). A multi-model and multi-index evaluation of drought characteristics in the 21st century. *Journal of Hydrology*, *526*, 196–207.

Trenberth, K. E., Dai, A., Van Der Schrier, G., Jones, P. D., Barichivich, J., Briffa, K. R., & Sheffield, J. (2014). Global warming and changes in drought. *Nature Climate Change*, *4*(1), 17–22.

Tsakiris, G., & Vangelis, H. (2005). Establishing a drought index incorporating evapotranspiration. *European Water*, *9*(10), 3–11.

United Nations. (2018). Land and drought. UNCCD. Retrieved from http://www2.unccd.int/issues/land-and-drought

van der Molen, M. K., Dolman, A. J., Ciais, P., Eglin, T., Gobron, N., Law, B. E., … Chen, T. (2011). Drought and ecosystem carbon cycling. *Agricultural and Forest Meteorology*, *151*(7), 765–773.

van Lanen, H. A., Fendeková, M., Kupczyk, E., Kasprzyk, A., & Pokojski, W. (2004). Flow generating processes. In *Hydrological drought. Processes and estimation methods for streamflow and groundwater* (Vol. 48, pp. 53–96). Amsterdam, Netherlands: Elsevier.

Van Lanen, H. A. J., & Peters, E. (2000). Definition, effects and assessment of groundwater droughts. In *Drought and drought mitigation in Europe* (pp. 49–61). Dordrecht, Netherlands: Springer.

Van Loon, A. F. (2015). Hydrological drought explained. *WIRES Water*, *2*(4), 359–392.

Van Loon, A. F., Gleeson, T., Clark, J., Van Dijk, A. I., Stahl, K., Hannaford, J., … Hannah, D. M. (2016). Drought in the Anthropocene. *Nature Geoscience*, *9*(2), 89–91.

Van Loon, A. F., & Laaha, G. (2015). Hydrological drought severity explained by climate and catchment characteristics. *Journal of Hydrology*, *526*, 3–14.

Van Loon, A. F., Stahl, K., Di Baldassarre, G., Clark, J., Rangecroft, S., Wanders, N., … Uijlenhoet, R. (2016). Drought in a human-modified world: Reframing drought definitions, understanding, and analysis approaches. *Hydrology and Earth System Sciences*, *20*, 3631–3650.

Van Loon, A. F., Van Huijgevoort, M. H. J., & Van Lanen, H. A. J. (2012). Evaluation of drought propagation in an ensemble mean of large-scale hydrological models. *Hydrology and Earth System Sciences*, *16*(11), 4057–4078.

Van Loon, A. F., & Van Lanen, H. A. J. (2013). Making the distinction between water scarcity and drought using an observation-modeling framework. *Water Resources Research*, *49*(3), 1483–1502.

Van Rooy, M. P. (1965). A rainfall anomaly index independent of time and space. *Notos*, *14*(43), 6.

Vicente-Serrano, S. M., Beguería, S., & López-Moreno, J. I. (2010). A multiscalar drought index sensitive to global warming: The standardized precipitation evapotranspiration index. *Journal of Climate*, *23*(7), 1696–1718.

Vins, H., Bell, J., Saha, S., & Hess, J. (2015). The mental health outcomes of drought: A systematic review and causal process diagram. *International Journal of Environmental Research and Public Health*, *12*(10), 13251–13275.

Wada, Y., Van Beek, L. P., Wanders, N., & Bierkens, M. F. (2013). Human water consumption intensifies hydrological drought worldwide. *Environmental Research Letters*, *8*(3), 034036.

Wagner, W., Hahn, S., Kidd, R., Melzer, T., Bartalis, Z., Hasenauer, S., … Komma, J. (2013). The ASCAT soil moisture product: A review of its specifications, validation results, and emerging applications. *Meteorologische Zeitschrift*, *22*(1), 5–33.

Wan, W., Zhao, J., Li, H. Y., Mishra, A., Leung, L. R., Hejazi, M., … Wang, H. (2017). Hydrological drought in the Anthropocene: Impacts of local water extraction and reservoir regulation in the US. *Journal of Geophysical Research: Atmospheres*, *122*(21), 11313–11328.

Wang, D., Hejazi, M., Cai, X., & Valocchi, A. J. (2011). Climate change impact on meteorological, agricultural, and hydrological drought in Central Illinois. *Water Resources Research*, *47*(9), 1–13.

Wang, L., & Yuan, X. (2018). Two types of flash drought and their connections with seasonal drought. *Advances in Atmospheric Sciences*, *35*(12), 1478–1490.

Wang, L., Yuan, X., Xie, Z., Wu, P., & Li, Y. (2016). Increasing flash droughts over China during the recent global warming hiatus. *Scientific Reports*, *6*, 30571.

Wang, Z., Zhong, R., Lai, C., Zeng, Z., Lian, Y., & Bai, X. (2018). Climate change enhances the severity and variability of drought in the Pearl River Basin in South China in the 21st century. *Agricultural and Forest Meteorology*, *249*, 149–162.

Weghorst, K. (1996). The reclamation drought index: Guidelines and practical applications. *Proceedings of the North American Water and Environment Congress & Destructive Water* (pp. 637–642), Denver, CO.

Wei, W., Li, W., Deng, Y., & Yang, S. (2019). Intraseasonal variation of the summer rainfall over the southeastern United States. *Climate Dynamics*, *53*, 1171–1813.

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 Resources Management*, *21*(5), 763–774.

Wolf, S., Keenan, T. F., Fisher, J. B., Baldocchi, D. D., Desai, A. R., Richardson, A. D., … Peters, W. (2016). Warm spring reduced carbon cycle impact of the 2012 US summer drought. *Proceedings of the National Academy of Sciences*, *113*(21), 5880–5885.

Woodhouse, C. A., & Overpeck, J. T. (1998). 2000 years of drought variability in the Central United States. *Bulletin of the American Meteorological Society*, *79*(12), 2693–2714.

Wu, R., & Kinter, J. L., III. (2009). Analysis of the relationship of US droughts with SST and soil moisture: Distinguishing the time scale of droughts. *Journal of Climate*, *22*(17), 4520–4538.

Wu, Z. Y., Lu, G. H., Wen, L., & Lin, C. A. (2011). Reconstructing and analyzing China's fifty-nine year (1951–2009) drought history using hydrological model simulation. *Hydrology and Earth System Sciences*, *15*(9), 2881–2894.

Xiao, J., Zhuang, Q., Liang, E., Shao, X., McGuire, A. D., Moody, A., … Melillo, J. M. (2009). Twentieth-century droughts and their impacts on terrestrial carbon cycling in China. *Earth Interactions*, *13*(10), 1–31.

Yang, Y., Saatchi, S. S., Xu, L., Yu, Y., Choi, S., Phillips, N., … Myneni, R. B. (2018). Post-drought decline of the Amazon carbon sink. *Nature Communications*, *9*(1), 3172.

Yi, C., Pendall, E., & Ciais, P. (2015). Focus on extreme events and the carbon cycle. *Environmental Research Letters*, *10*(7), 070201.

Yoon, J. H., Mo, K., & Wood, E. F. (2012). Dynamic-model-based seasonal prediction of meteorological drought over the contiguous United States. *Journal of Hydrometeorology*, *13*(2), 463–482.

Yu, Z., Wang, J. X., Liu, S. R., Rentch, J. S., Sun, P. S., & Lu, C. Q. (2017). Global gross primary productivity and water use efficiency changes under drought stress. *Environmental Research Letters*, *12*(1), 1–10.

Yuan, X., Ma, Z., Pan, M., & Shi, C. (2015). Microwave remote sensing of short-term droughts during crop growing seasons. *Geophysical Research Letters*, *42*(11), 4394–4401.

Yuan, X., Wang, L., & Wood, E. F. (2018). Anthropogenic intensification of southern African flash droughts as exemplified by the 2015/16 season. *Bulletin of the American Meteorological Society*, *99*(1), S86–S90.

Zhan, W., Guan, K., Sheffield, J., & Wood, E. F. (2016). Depiction of drought over sub-Saharan Africa using reanalyses precipitation data sets. *Journal of Geophysical Research: Atmospheres*, *121*(18), 10–555.

Zhang, Q., Li, Q., Singh, V. P., Shi, P., Huang, Q., & Sun, P. (2018). Nonparametric integrated agrometeorological drought monitoring: Model development and application. *Journal of Geophysical Research: Atmospheres*, *123*(1), 73–88.

Zhang, X., Tang, Q., Liu, X., Leng, G., & Li, Z. (2017). Soil moisture drought monitoring and forecasting using satellite and climate model data over southwestern China. *Journal of Hydrometeorology*, *18*(1), 5–23.

Zhang, Y., You, Q., Chen, C., & Li, X. (2017). Flash droughts in a typical humid and subtropical basin: A case study in the Gan River Basin, China. *Journal of Hydrology*, *551*, 162–176.

Zhao, M., Velicogna, I., & Kimball, J. S. (2017). Satellite observations of regional drought severity in the continental United States using GRACE-based terrestrial water storage changes. *Journal of Climate*, *30*(16), 6297–6308.

Zhao, T., & Dai, A. (2015). The magnitude and causes of global drought changes in the twenty-first century under a low–moderate emissions scenario. *Journal of Climate*, *28*(11), 4490–4512.

Zhu, E., Yuan, X., & Wood, A. W. (2019). Benchmark decadal forecast skill for terrestrial water storage estimated by an elasticity framework. *Nature Communications*, *10*(1), 1237.

Zhu, Y., Wang, W., Singh, V. P., & Liu, Y. (2016). Combined use of meteorological drought indices at multi-time scales for improving hydrological drought detection. *Science of the Total Environment*, *571*, 1058–1068.

How to cite this article: Haile GG, Tang Q, Li W, Liu X, Zhang X. Drought: Progress in broadening its understanding. *WIREs Water*. 2020;7:e1407. https://doi.org/10.1002/wat2.1407