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REVIEW PAPER

Drought indices and indicators revisited

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Abstract

There are numerous drought indicators used by decision makers all around the globe which have been developed to fulfill specific needs. By far, risks associated with drought and related consequences have become a bold topic for scientists in which debates still taking place everywhere. No global drought indices could provide universally accepted results since almost all of these indices are based on observed data as key performance indicators. In this respect, researchers spend a lot of effort on this issue for a better understanding on the various indices which are proposed until now. It is crucial to get a better sense on how drought can develop and how it can be monitored. It is also important to understand that, recent global challenges like climate change also amplifies the obligation on continues effort toward developing better indicators and methods to monitor droughts. As climate patterns change or a seasonal shift occurs, predefined drought indicators become useless. In this review, the concepts of drought indices and indicators are revisited and evaluated. Pros and cons of frequently used indices are addressed and the major differences between them are bolded. It is concluded that each index is applicable to fulfill expectations of a specific drought type while pre-knowledge about each case is very crucial. However, there is a need to develop a composite drought index to integrate all relevant data and drought definitions, with respect to the dominant types of monthly droughts in time and space together with climate change scenarios.

Keywords Drought indices · Climate change · Meteorology · Rainfall failure · Drought risk · Arid region

Introduction

Definition of drought

Since droughts become more common worldwide, debates on the definition and perspectives of the drought become more tangible and there is no globally accepted standard definition for drought. Even among drought experts, a single definition of drought is hard to agree on. To brief these individuals, a deficit in precipitation from an expected mean within a time frame can be identified as drought (Svoboda et al. 2002; Sheffield and Wood 2012; Eslamian 2014; Yihdego 2016; Yihdego and Eslamian 2016; Yihdego and Webb 2016; Yihdego et al. 2016, Azmi et al., 2016). Hence, one needs to realize the context in which the drought and its impacts are expressed. Wilhite and Glantz (1985) identified more than 150 realization of drought in the literature; while from those, drought can be classified into four major types: (i) meteorological, as a reduction in precipitation; (ii) agricultural, as a lack of moisture in soil; (iii) hydrological, tracked down considering the decline in stream-flows and runoffs; and finally (iv) socioeconomic droughts in human water use while there is also another definition of drought based on ecological water deficit in the environment as ecological drought (Yihdego

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et al. 2017). Based on these definitions, there are diverse and different realizations of drought types which have several impacts on different sectors.

Types of droughts

All types of drought initiate with the deficit in precipitation over time and/or space, while an early stage of accumulating deficiency in precipitation referred commonly to a meteorological drought, persistence of the phenomenon over time, i.e., considering above-normal temperatures, high winds, and low relative humidity, with great impacts on socioeconomic and environmental cycles. Since regions have various climatic patterns, meteorological droughts are expressed with changes in the local hydro-meteorological, geographical, and climatological situation which plays an important role in definition of the meteorological drought. Meteorological droughts can develop rapidly, but they also can end up as quickly as if deficits in the precipitation are relatively small. However, these types of droughts may also linger into a multi-seasonal event and/or develop to the other types of droughts.

Agricultural droughts can be categorized as the developed meteorological drought where there is a precipitation deficit during the growing season; such that crop growth and development is restrained (Eslamian 2014). Agricultural droughts are events which become the next phase of meteorological droughts. As the name implies, a drought of which its characteristics extend in time to the point which the agricultural demands of a region are affected by lack of moisture in the soil. Agricultural droughts may extend far beyond the portions of a growing season. However, the natural break between seasons can be recognized as a period which drought did not improve or became severe, assuming no agricultural production was taking place. Agricultural drought can also precede the actual initiation of the growing season while situations are not in favor of planting.

Hydrological drought refers to drought events which curtail the amount of available water in water resources (Eslamian 2014). Since meteorological droughts last long, the lack of surface flow based on dryness of soil begins to affect the hydrology of the region. Commonly, there exist lags in which they are unique in time and space. Hence, hydrological impacts of drought on a region could not be monitored immediately right after the initiation. As a result, after the extension of a dry period in a region, soil moisture, streamflow, subsurface recharge, and the amount of water in the hydrologic cycle would decline. During winter months, frozen precipitation is accumulated for future runoff; hence, a dry winter can induce hydrologic drought in upcoming months. Even with precipitation events, the dry soil can inhibit substantial runoff, as it will captivate excessive moisture before reaching to rivers, streams, and water bodies. Dryness and heat will incorporate to decrease the available water within a hydrological system. As for some hydrological systems, water managers can choose to withhold water if hydrologic drought is of the concern to reduce or to moderate future impacts. Without proper recharge, a long-term drought will affect the hydrology of a region even if precipitation returns back to its normal situation. It typically takes the longest period for a hydrological drought to develop and, in turn, the recovery time can also linger to months or even years. Socioeconomic definitions of drought associate with the relation of supply-demand and economic goods regarding the elements of meteorological, agricultural, and hydrological droughts. It differs from the types of drought, since its occurrence depends on the spatiotemporal processes of supply and demands (Wilhite and Glantz 1985). Other weather or climate factors not only can be used to express why certain goods are scarce, but also it can interpret why socioeconomic drought or demand for such goods exceeds supplies. Impacts of socioeconomic drought can develop immediately once drought is upon a region and may linger for quite some time depending on the severity of the impact and the value of the impacted goods. Ecological drought can also be defined as a prolonged and widespread deficit in naturally available water supplies, i.e., changes in natural and managed hydrology, which creates multiple stresses in an ecosystem. As an example, ecological water level of a lake, as the lowest water level needed for a natural retention, integrity, and function of a lake ecosystem (Liu et al. 2012) can easily be affected with the presence of ecological droughts in the region.

How to monitor drought

Considering the hardship in definition of droughts, it is vital to know how they develop and what indicators are in hand to determine those phenomena. Thus, gathering information about the primary weather and climate characteristics of a region should be the first step in studying droughts. One should have a pre- and post-information about the climatology of the region to maintain and define the probability of ongoing or past drought events. A regular climatic behavior in time and/or space may also be a sign for the initiation of drought in another region. Thereby, any core observation must first deal with the climate of the region to specify if the current condition is developing toward a drought in the future. The possibility of proper planning would rise to mitigate impacts of the probable drought assuming a pattern of dry weather is unique. In addition, drought early warning system (DEWS) focused on monitoring drought condition is an important part of being adequately prepared for any drought event (Wilhite 2005, 2009; WMO 2011; Eslamian 2014). Without adequate planning and preparedness, the consequences of drought may exacerbate or lead to even more severe consequences in different sectors.

With the basic characteristics of drought such as lack, or deficit of precipitation, it is critical to have reliable and long-term records of precipitation. Most drought monitoring operations, as part of a DEWS, are established with the knowledge of comparing recent weather events with the archives. Even though precipitation is the corner stone of many drought indicators, the presence of other indicators is important in assessment of drought severity. Ideally, one should try to monitor rivers and streams, snowpack, water storage, ecological health of the area, soil moisture, evaporation, crop production, and other indicators which might be vital in understanding water availability and use in the study area. For many regions, it may not be possible to look at every single indicator, determining if an area is dealing with a drought, mostly due to quality and quantity of the available information. However, it is more acceptable to look at multiple indicators to verify the existence and severity of drought. Regardless of the type of indicator used in the analysis, dealing with the longest, gap-free, and reliable record would be helpful in establishing the context of current and historical conditions. It is crucial to understand that a drought is a feature category of dry side of a region expressed in spatial and temporal availability of precipitation. Those events which are defined as statistically extreme in an allocated distribution will be better understood if more of them fall within the sample size. Guttman (1993, 1999) recommended that at least 50 years of precipitation data record is the minimum information needed to define and analyze long-term or seasonal drought periods, while more information is needed for droughts to cover multiple years (i.e., when using the Standardized Precipitation Index (SPI)).

The pressing issue is that some indicators may not have a long enough period of records, and this is especially associated with the remotely sensed data. Proper monitoring of a drought requires time and energy to reconstruct the historical data records or develop data sets for as many data points as possible. However, in data reconstruction, the information loss of the desired data set is another issue to take care of. Once a study is completed, monitoring current conditions not only adds to the period of record but also allows researchers to learn about the climate of the region intimately. This is important to understand as it may be more meaningful if monitoring current conditions is known for how much precipitation is expected over the period of the observation. If the precipitation distribution for a region is typically seasonal, then a shortage in precipitation during this period would not necessarily define the beginning of a drought. Thus, it is possible to determine the crucial period(s) of precipitation for any region.

Drought indicators and indices

An *indicator* is a scale of a meteorological, hydrological, agricultural, or socioeconomic variable that provides an indication of potential drought-related stress or deficiency. An *index* determination is a method of deriving “value-added” information linked to drought by comparing current conditions with the historical information (Eslamian 2014; Yihdego 2015, 2016; Hao and Singh 2015; Yihdego and Eslamian 2016; Yihdego et al. 2016, Azmi et al. 2016). Indices are attempts to quantify droughts and their magnitude while it is important to note that these indices are indicators as well. For some, the quickest and easiest way to determine drought is by comparing actual precipitation to a long-term average. The percent of normal method allows for a calculation that can be computed over any defined period and gives meaning to the recorded values. While having some drawbacks, this method is applied by taking the difference between the mean and median of the data set; but it can be significantly different for shorter periods of time. Thus, comparison of precipitation departures of mean or normal amount may be misleading. Keeping in mind that the simplest method is not necessarily the best and vice versa, scientists require a better way of determining the moments of the distribution associated with precipitation while giving some historical context to the frequency of an event. For this aim, drought indices were developed to express droughts in a manner that provides more information than just how the current situation compares with the historical average and identification of water shortage associated with an event duration and intensity. Heim (2002) showed the evolution of drought indices (DI) from the early 1900s to what has become the standard for the USA with the development of the US Drought Monitor in 1999. Table 1 shows major twentieth century US drought indices which were addressed by Heim. Heim also mentioned that the drought indices were designed based on local or regional definition of drought in time and space such as 15 consecutive days with no rain, more than 21 days with precipitation less than one third of the normal expectancy, annual precipitation less than 75% of normal expectancy, monthly precipitation lower than 60% of normal expectancy, and finally any rainfall less than 85% of normal expectancy. Heim also referred to Blumenstock Index (Blumenstock 1942) and compared it with other indices, showing that different indices produce different realizations of drought. It was concluded that both Blumenstock’s and Munger’s indices (Munger 1916) are best used to measure short-term droughts.

Very similar to these compassions, earlier works of Blumenstock (1942), Condra (1944), Friedman (1957), Dickson (1958), Dracup et al. (1980), Frick et al. (1990a, b), Doesken and Garen (1991), Doesken et al. (1991), Guttman (1991, 1993, 1997, 1999), Garen (1993), Gommes and Petrassi (1994), Easterling (1996), Fernandez and Salas (1999a, b), and many other researchers on drought indices applied in the USA were addressed by Heim (2002). It should be noted that the progression of the development of indices is

Table 1 Drought indices discussed by Heim (2002)

Indices	Details on applications
Munger's Index	A period without 24-h precipitation of 1.27 mm
Kincer's Index	≤30 consecutive days with less than 6.35-mm precipitation of 24 h
Marcovitch's Index	Temperature and precipitation used
Blumenstock's Index	Precipitation within 48 h
Antecedent Precipitation Index	Precipitation used
Moisture Adequacy Index	Precipitation and soil moisture used
Palmer's Index (PDSI and PHDI)	Precipitation and temperature used in water balance
Crop Moisture Index	Precipitation and temperature used in water balance
Keetch–Byram Drought Index	Precipitation and soil moisture used in water balance
Surface Water Supply Index	Snowpack, storage of reservoir, runoff, and precipitation
Standardized Precipitation Index	Precipitation used
Vegetation Condition Index	Satellite AVHRR radiances used
Drought Monitor	Integrates several drought indices together

aimed at trying to end up with a number or value (i.e., usually a dimensionless value) that has meaning in the expression of drought severity. Some drought indices focus strictly on agricultural issues while others focus on water supply or water availability in the region. When Wayne Palmer (1965) developed the Palmer Drought Severity Index (PDSI); it was an attempt to incorporate water balance in a regional perspective in order to identify episodes of meteorological and agricultural droughts. Since then, other indices were developed based on the concept of more recent realization of droughts. For instance, Hao and AghaKouchak (2013, 2014) introduced a multivariate standardized drought index (MSDI) based on copulas concept. The new index combines the SPI and the Standardized Soil Moisture Index (SSI) for drought characterization probabilistically. A more recent study by Hashemi Nasab et al. (2018) is based on the application of machine learning on drought indices. A so-called Fuzzy Integrated Drought Index (FIDI) was introduced as a combination of most effective factors in developing drought and compared with Precipitation Anomaly Percentage Index (PAPI), actual Evapotranspiration Anomaly Percentage Index (EAPI), Runoff Anomaly Percentage Index (RAPI), and Soil Moisture Anomaly Percentage Index (SMAPI) and found quite handy in application.

As other drought indices were developing, it is obvious that all indices are not applicable everywhere since many were developed to address a problem in a certain climate. As some indices are in needs for great amount of data records and need complex procedures, the World Meteorological Organization (WMO) wanted to put forward a recommendation for a single meteorological drought index. This attempt was to develop a method to be the minimum standard and starting point for every country in assessment of drought providing more comparability between regions. At a meeting in 2009, "Lincoln Declaration on Drought Indices" of the SPI was recommended as the drought index to be computed and used globally by meteorological and hydrological services as the common meteorological drought index (WMO 2011). As efforts toward developing drought indices carry on, knowledge of which indices are best and more applicable in a region becomes critical in establishing a functional DEWS. Due to Tsakiris et al. (2007) using drought indices is prevalent while a lot of methodologies for drought characterization exist. Keyantash and Dracup (2002), Heim (2002), Mishra and Singh (2010), Dai (2011), and Zargar et al. (2011) are among the researchers that recently reviewed the drought indices and compared them with each other. Zargar et al. (2011) introduced drought as a stochastic natural hazard which arise by severe and continuous deficit of precipitation. It is also shown that drought indices are measures which specify drought stages by assimilating values from one or several sets such as precipitation and evaporation into a numerical value. According to this study general sequence of different drought types can be concluded as modification on National Drought Mitigation Center (NDMC) of University of Nebraska, USA (NDMC 2006a, b, c).

It is beneficial to focus on the various applications of which these indices are likely to be used in evaluating and selecting various droughts. Most of the drought indices have the potential of multiple applications, or even can be applied to various sectors. More recently, WMO together with Global Water Partnership (GWP) published the handbook of drought indices with a focus on definition and methodology of drought indices that seeks to support regions and countries in developing countries (WMO and GWP 2017). Interested reader about drought categorization and classification can also refer to WMO and GWP (2017) for more details. The drought indices described in this study are by no means complete; however, discussion on some of indices which are most commonly applied globally on meteorological, agricultural, and hydrological analyses is addressed in the following part.

Standardized precipitation index

Even before the WMO recommendation in 2009, the SPI received a lot of attention around the world as countries were in need to calculate and use it operationally to track drought conditions of their own. The SPI was developed by McKee et al. (1993). It uses the historical precipitation records in space and a probability of precipitation is developed for various time lengths. The intensity scale for SPI has both a positive and negative values, where the positive values are linked to surplus and the negative values are used to identify deficit events. McKee et al. (1993) also characterized drought events as initiating when the SPI value fell below − 1.0 for a period (Table 2). The duration of the drought event lasts until the SPI became positive. This is where the SPI has a great amount of utility. SPI is flexible and can be calculated for both short- and long-term periods by defining different time intervals. Another reason for the SPI's appeal is that the index can be calculated with presence of missing data. The way that the SPI is calculated, the distribution can still be developed and used. If too many data are missing, results would be "null" and a computer will pass to the next SPI value when enough data are available. Primarily, the SPI was calculated for periods of 1–72 months, but it is mostly used for periods of 24 months or less. This flexibility allows SPI to be very handy in monitoring meteorological, agricultural, and hydrological droughts in which time scales and impacts are various. Effect of time on precipitation deficit gradually and variably affects different water resources, the multitude of SPI durations can be used to show changes in different water features as given in Table 3 (Zargar et al. 2011; NDMC 2006c).

Frequently used in the literature SPI is applied in many studies all around the world while Bonaccorso et al. (2003), Tsakiris and Vangelis (2004), Moreira et al. (2006), Daneshvar et al. (2013), Li et al. (2014), Huang et al. (2015), Karabulut (2015), Chang et al. (2016), Jiang et al. (2017), Salehnia et al. (2017), Mohammad et al. (2018), and Rahman and Dawood (2018) can be mentioned as some of these studies.

Standardized Precipitation Evapotranspiration Index

One of the more recently developed drought indices is the Standardized Precipitation Evapotranspiration Index (SPEI), which catches the basic premise of the SPI and added a temperature component to capture a simplified water balance (Vicente-Serrano et al. 2010; Yihdego and Webb 2016). The SPEI, like the PDSI, uses a simple water balance calculation that is based on the Thornthwaite (1948) model for evaluating the potential evapotranspiration (PET). Several studies have shown that good estimates of PET can be obtained with various meteorological parameters, but in the context of drought index, they are not needed since a general estimation of the water balance is adequate. This also keeps the calculations parsimonious while giving the additional data requirements needed for determining actual evapotranspiration. It has the potential to track agricultural drought more efficiently. In this respect, some of drought studies based on SPEI are conducted by Potop and Mozny (2011), Xu et al. (2013), Stagge et al. (2015), and Alam et al. (2017).

Table 3 Different types of SPI and their applications (source: Zargar et al. 2011)

Time length and duration (month)	Application
Short (1)	Soil moisture and crop stresses
Short and medium (3)	Seasonal prediction of precipitations
Medium (6)	Effectively representing the precipitation over distinct seasons.
Medium (9)	If SPI 9 is less than − 1.5, then it is an applicable indication in substantial impacts which can occur in agriculture area
Long (12)	Possibly tied to streamflow, reservoir water levels, and groundwater levels

Palmer Drought Severity Index

One of the most widely used indices is the Palmer Drought Severity Index, developed by Wayne Palmer for the United States Department of Agriculture in the 1960s (Palmer 1965, 1968). The index was predesignated to be used as an agricultural drought index. It measures the availability of moisture in the region monitored using a water balance equation. Unlike the SPI, which solely uses precipitation, the PDSI also incorporates temperature and soil moisture as well as a previous PDSI value. The temperature data is used to estimate PET, utilizing a Thornthwaite approach and the default soil moisture information comes from data that has been extrapolated from the soils information collected by the US Geological Survey (Palmer 1965). However, the complexity of the approach brought by other variables used in defining PDSI makes it more challenging to incorporate soils information. Like SPI, the PDSI has both a wet and dry categorization overview, with most values falling into a range between + 4

Table 2 The Standardized Precipitation Index classification scale (Guttman 1999)

SPI value	+ 2.0 ≤ SPI	+ 1.5~1.99	+ 1.0~1.49	− 0.99~0.99	− 1.0~− 1.49	− 1.5~−1.99	− 2.0 ≥ SPI
Moisture	Extremely wet	Very wet	Moderately wet	Near normal	Moderately dry	Severely dry	Extremely dry

and − 4 (Table 4). Having both scales in hand, it allows users to become familiar with how the PDSI responds to precipitation events to have a better realization of how the index reacts for any specific region. In literature, the agricultural applications of the PDSI have been widely used. Several inherent drawbacks are associated with using the PDSI, and these have been well documented (e.g., Hayes et al. 1999; Alley 1984, 1985; Steila 1972; Karl 1986). This index has a time scale of approximately 9 months, which leads to a lag in identification of the drought conditions based on the simplified soil moisture component within the calculations. The application of lags may be used up to several months, which is a drawback when trying to identify a rapidly emerging drought situation. There are also seasonal applications of the PDSI as it does not account for frozen precipitation and frozen soils satisfactorily. Thus, all precipitation events are assumed to be liquid precipitation events. Some of the drawbacks of using the PDSI are due to the reasons that it was developed to be used in the Midwest of the USA as an initiator to identify agricultural droughts. Several studies have discussed the limitations of the PDSI (e.g., Alley 1984; Karl and Knight 1985; Willeke et al. 1994; McKee et al. 1995; Guttman 1997), and they were summarized by Kangas and Brown (2007), which presented applications of using the PDSI for various drought episodes. Kangas and Brown (2007) also described the positive attributes of using the PDSI where the longevity of the index is accounted for. The index has been tested under different scenarios and illustrated the benefits of using precipitation, temperature, and soil characteristics in characterizing droughts. In this respect, some of the drought studies based PDSI are Sheffield et al. (2012), Cook et al. (2015), Weng et al. (2015), Hou et al. (2016), Dai and Zhao (2017), and Zhao and Dai (2017).

Crop Moisture Index

As the drawbacks to the original PDSI became apparent, Wayne Palmer came up with his Crop Moisture Index (CMI), which was introduced 3 years after the original PDSI (Palmer 1968). The CMI was designated to be an agriculture-only drought index which responded well to rapidly changing climate situations during the growing season. The CMI was developed for those areas of interest in the grain-producing sites in the USA in line with the previously studies of Wayne Palmer. The calculation of CMI need (i) total weekly precipitation and (ii) mean temperature together with the (iii) previous week's CMI value. A weighted output for each location is used, which allows for comparison between climate regimes. To respond rapidly for changing agricultural conditions, a simple difference between PET and moisture is used to characterize if the moisture was sufficient to offset what was lost in potential evapotranspiration; and in return, include it into soil moisture profile. Due to the targeted nature of what the CMI is monitoring, it is not a favorable index for long-term drought events. The CMI would respond rapidly to precipitation events, but can also provide a false sense of recovery from long-term droughts, as it improves in short term may which not necessarily means that the long-term situation is improved. Further for these studies, Narasimhan and Srinivasan (2005), Michaelian et al. (2011), Li et al. (2014), Martinez-Fernandez et al. (2016), and Pablos et al. (2017) are among those researchers which used scPDSI as a drought index in analysis.

Table 4 The Palmer Drought Severity Index classification scale (Palmer 1965)

4.0 ≤ PDSI	Extremely wet
3.0~3.99	Very wet
2.0~2.99	Moderately wet
1.0~1.99	Slightly wet
0.5~0.99	Incipient wet spell
0.49~− 0.49	Near normal
− 0.5~− 0.99	Incipient dry spell
− 1.0~− 1.99	Mild drought
− 2.0~− 2.99	Moderate drought
− 3.0~− 3.99	Severe drought
− 4.0 ≥ PDSI	Extreme drought

Self-Calibrated Palmer Drought Severity Index

One of the inherent problems associated with the PDSI was that comparisons were being made from the results of different regions, especially those with very different climate regimes, and in many cases, this was not suitable. The Self-Calibrated Palmer Drought Severity Index (scPDSI) is based on the original PDSI, while it takes all the constants and replaces them with values that are calibrated for the interested location (Wells et al. 2004). By considering the calculations of the scPDSI accounting for each region, this index becomes more reflective of what is happening at each site and allows for comparisons between regions to be more accurate. Using these assumptions, data can be computed at different time steps, and the extreme events being calculated by the scPDSI are indeed rare since they are based on calculations at that location and are not a constant. Studies by Sousa et al. (2011), Jin et al. (2016), Cook et al. (2016), and Vance et al. (2017) are among those typical cases of studies which used calibrated values of PDSI as an index of *sc*PDSI in their studies.

Deciles

Deciles of precipitation are another approach to characterize the departure of precipitation from a long-term normal or average, which was developed to identify and classify droughts. Gibbs and Maher (1967) tried on eliminating the drawbacks of using the percent of normal calculations in classifying droughts in Australia. Using deciles, current precipitation is ranked against the historical records. This method is based on breaking the historical records into several partitions that are 10% of the record. The first decile would be precipitation falling in the driest 10% of the record and the 5th decile would be the median (Table 5).

Although the simplistic nature of this approach is attractive, it needs a long-term period of records in practice. The straightforward nature automatically defines the conditions of the dryness for a region, allowing researchers to understand exactly where the current precipitation regime interacts historically. Those implementing of the method would have certain deciles that are thresholds which triggers some responses. Having the deciles method as part of a DEWS established when a drought begins and/or ends, it is based on the data and characteristics of drought in the region, by defining the thresholds that are used. With the flexibility of establishment of the thresholds on the climate of the region, the deciles method can be used to monitor all types of drought, as it has been applied to monitor both agricultural and hydrological droughts. For instance, studies of Salehnia et al. (2017) can be named as one of the samples of using deciles in drought analysis.

Surface Water Supply Index

One of the previously mentioned drawbacks of the PDSI was the miss-consideration of frozen precipitation in the calculations. This problem was addressed particularly in the Surface Water Supply Index (SWSI) in the early 1980s by Shafer and Desman (1982). For this aim, the SWSI is used primarily as a hydrological drought index, to address the shortcomings of PDSI. This issue was addressed by considering snowpack of the mountainous regions along with the subsequent runoff from the melting snow ending to the river streams. In this respect, four inputs were required for the calculations as precipitation, reservoir storage, snowpack, and streamflow. The inputs were given weighted values based on the total contributions to the water balance in the basin while the scaling is very similar to the PDSI ranging between + 4.2 and − 4.2. Even with the advantages that the SWSI presents over using the PDSI, some issues limit its widespread application. Since many inputs are not available for many locations, or need to be calculated individually, usually data points are added or omitted over the basin to assign weights for re-adjustments. It would be difficult to make comparisons between different cases of study being the calculations are unique for each study area. It is also beneficial to be aware that the SWSI is not applicable for decision makers in all basins since issues like water withheld for diversion or management practices are regular in many basins. Interested readers on SWSI can refer to various cases of studies, e.g., Kwon and Kim (2010), Steinemann et al. (2015), Zeynolabedin et al. (2016), and Ofwono et al. (2017).

Table 5 The Deciles classification table (Kinninmonth et al. 2000)

Decile level	Moisture level
1–2: lowest 20%	Much below normal
3–4: next lowest 20%	Below normal
5–6: middle 20%	Near normal
7–8: next highest 20%	Above normal
9–10: highest 20%	Much above normal

Other indices

Over the years, many drought indices have been developed. Some were developed for a very specific area while others were developed to address a certain type of drought. There have been new types of data and platforms that have augmented and added to drought monitoring efforts along with the various available indices. One of the recent platforms being utilized for monitoring and detecting drought has been via the integration of remotely sensed data. Accordingly, indices like SPI can be calculated using data for various satellite platforms to determine the degree of dryness in time and space. The advantage of using remotely sensed data is to allow for a higher spatial coverage resolution that can help to fill in the gaps of in situ data and which are also updated frequently to allow near real-time analyses. There are also hybrid types of indices where satellite data are being merged with surface data to determine if the stress being observed in the vegetation could be due to drought conditions instead of disease, pests, etc. For instance, the Vegetation Drought Response Index (VegDRI) considers climate-based drought indices as well as satellite-derived data along with other biophysical parameters to determine drought-related stresses on vegetation through the utilization of data mining techniques (Brown et al. 2008). Depending on the data availability and quality in any area, it may possibly be utilized in many drought indices which are available. With enough communication and coordination, it may also be possible to replicate composite approaches such as what is being done with the US Drought Monitor. Accordingly, recent studies of Hassanzadeh et al. (2011), Eslamian et al. (2012), Fakhri et al. (2012), Jin and Wang (2016), Azmi et al. 2016, and Hazaymeh and Hassan (2017) are among several examples of using different types of drought analysis indexes including statistical multivariate analysis, satellite imagery, and remote sensing.

Pros and cons of the selected drought indices

Many studies have indicated that no single drought index (DI) can perform appropriately in all circumstances, and that most individual DIs cannot comprehensively evaluate the water stress conditions of a single terrestrial ecosystem. To overcome these drawbacks, a number of studies suggested to make use of combination and aggregation approaches to derive new DIs, ultimately leading to more accurate and reliable indices than individual DIs alone (Gocic and Trajkovic 2014; AghaKouchak et al. 2015; Hao and Singh 2015; Azmi et al. 2016; Flint et al. 2018). The main aim of these approaches is to develop an inclusive DI that is more accurate and reliable than the individual DIs. Some of the most common combination- and aggregation-based used blending of subjective and objective DI; others use linear or multivariate combinations of DIs.

Different individual DIs provide different, if not conflicting, information under various climate conditions, land use, and the perspective of the application. Therefore, no single DI fits appropriately in all different circumstances. The main drawbacks of aggregation-based DIs are the subjectivity of the analysis, limited statistical and mathematical frameworks to objectively link or combine a variety of DIs from different drought types. The validation of any new DIs will be simply comparing the new indices with the traditional and DIs (Azmi et al. 2016).

Missing data issues are usually a typical problem in countries which are trying to develop drought monitoring activities since consistent, reliable, and long-term precipitation records are not available. As a result, even with the existence of data breaks in the SPI results, these records can be utilized in deriving favorable information. By using this index, one would be provided with time intervals that would make the most sense on the severity and the type of drought associated with study area. Since the SPI is a precipitation-based index, it tends to be used more often to identify periods of meteorological and hydrological droughts which does not have a water balance component. There are agricultural drought applications where the SPI is useful; especially when identifying a developing drought situation. Hence, the SPI with a short-time scale will respond quickly to a situation where conditions are drying out rapidly. Therefore, the flexibility of the SPI is in the availability of calculation for any period, and this feature makes it possible to calculate a SPI that would be helpful in application.

Having the same flexibility that the SPI has, SPEI enables a weekly update using a moving time window while the SPEI uses the difference between the basic calculations for PET and precipitation to determine a wet or dry period. Given the flexible nature of the SPEI, it has the capacity to be utilized in monitoring the various types of droughts due to incorporation of water balance.

Drought indices in a changing climate

The idea of what a changing climate mean and how to address it can be monitored using recent discussions and debates in literature. Not only the written climate records but also by considering the paleo-climatic data, it is possible to understand the characteristics of past droughts. What is certain is that the drought has been a constant phenomenon with episodes taking place regularly during history. Some events have been short, while others have lingered for multiple decades. In the context of a changing climate, it should be noted that the droughts will continue to occur, as they are natural climate cycle of the globe. While droughts can have different causes depending on the area of the world and other natural factors, most scientists started to link more intense droughts to climate change. That is because as more greenhouse gas emissions are released into the atmosphere, air temperature increases and more moisture evaporates from land and water resources occurs. Warmer temperatures also increase evaporation in plant soils, which affects plant life and can reduce rainfall events. When rainfall does come to drought-stricken areas, they are less able to absorb the water which increases the likelihood of flash floods. With increasing temperatures and uncertainty in amount and distribution of precipitation, changes in intensity, duration, and frequency of droughts are likely to increase for many locations (Easterling et al. 2000; Meehl et al. 2007; IPCC 2013; Fuchs et al. 2014; Escalante-Sandoval and Nunez-Garcia 2017). With this knowledge in hand, it is important to recognize the value of those drought indices that include a temperature component, as water balance for an area would not be dependent on precipitation alone. Drought indices that also account for temperatures can also be helpful for properly showing the impact of temperature on water balance. By using approaches like the methodology which is suggested by the US Drought Monitor in considering all the available indicators would also allow for the flexibility to implement more temperature-based indicators. A researcher may also need to continue working toward newer and potentially better drought indices that are needed to account for a changing climate in which there may be a shift in both temperature and precipitation regimes. Over time, there have been many approaches to identify, classify, and monitor droughts. A recent study by Vazifehkhah and Kahya (2018) used North Atlantic Oscillation (NAO) and Arctic Oscillation (AO) together with Standardized Streamflow Index (SSFI) over Turkey and Northern Iran. It was concluded that the effect of each oscillation is not permanent and negative extreme phases of NAO and AO could affect the hydrological drought stronger but in a shorter period compared to the longer period which is affected by positive phase of NAO and AO. Hence, as the world's climatic conditions change; some of those approaches may not work under new climate regimes, and the science community needs to continue to examine new approaches to capture observed changes. By doing so, indicators and indices will remain a vitally important component of any drought early warning system.

Similarly, data fusion-based drought index (DFDI) has been developed and its performance was analyzed for three different locations in Australia (Azmi et al. 2016). The DFDI comprehensively considers all types of drought through a selection of indices and proxies associated with each drought type. This index was used to monitor water stress conditions of terrestrial ecosystems by objectively linking water availability and vegetation conditions. The combination methodology makes use of advanced statistical methods and the eco-meteorological characteristics of an area to determine the ultimate water stress conditions at each time step. The validity of the new DFDI approach to generalize a range of DIs was tested for three case study areas, each with different combinations of land use and climate regimes (Azmi et al. 2016). More research is needed on how to combine and aggregate different DIs for better decision-making in water resources management especially under climate change scenarios. Particularly, statistical and multivariate analysis linked with climate change models can be an effective tool to address this important area of research.

Conclusions

There are many ways to identify drought episodes using a variety of indicators and indices. A universally accepted definition of drought has not been agreed on until now. There is a need for a comprehensive, robust, and simple drought index for an improved water resources management and planning. Nonetheless, evaluation and monitoring of water stress over a terrestrial ecosystem is much more complicated than using single drought indices.

With the variety of ways to explain drought, the simplest is to describe it as a deficiency of precipitation over a defined period. Scientists have also explained drought by the impacts being experienced. Over time, scientists have tried to better clarify droughts by developing various indices in which the duration and intensity of drought could be identified based on historical events. With the advent of various drought indices, it has also become evident that some indices will work better in certain situations than others. Numerous indices are available, and just the most used indices were discussed in this review. With all the indices available, new indices are being developed to address an unmet need. In the case of the SPEI, this index was developed to directly address how an increase in temperature that would impact drought in a changing climate by including a temperature component to the calculations. It is unknown exactly how droughts will evolve in the future, and some of the techniques we use to monitor and assess droughts today may not be adequate. While droughts can have different causes depending on the area of the world and other natural factors, most scientists have started to link more intense droughts to climate change. That is because as more greenhouse gas emissions are released into the atmosphere, air temperatures increase, and more moisture is taken away from the surface and groundwater. Warmer temperatures also increase evaporation in plant soils, which affects plant life and can reduce rainfall events more frequently. When rainfall does come to drought-stricken areas, the drier soils it hits are less able to absorb the water which may explain the increase of flash flooding in arid regions.

To be considered in this respect, more research is needed to aggregate the existing DIs into a combined DI that is comprehensive and easy to use taking into account the new climate change scenarios in water resources planning and management. For this aim, studies based on previous works considering similarities between regions would be an interesting topic for future researches.

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