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REVIEW ARTICLE

Review of Drought Characterization Indices

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Abstract
Planning and managing agricultural operations and water resource systems require an in-depth understanding of the drought phenomenon. Since the 1960s, scientists have introduced a significant variety of drought indices to characterize droughts. The purpose of the present study is to review drought concepts and to aware researchers and policymakers on widely using drought indices. In this paper, some of the commonly used drought indices, their input requirements, applications, benefits, and drawbacks were reviewed. The original publications and several previous reviews were used in this comprehension. Widely using and operational drought indices were identified. Further, recently proposed drought indices to eliminate the limitations of earlier were tallied. Major operational and newer drought indices are emphasized with their input required, virtues, and demerits to be used in future drought characterization purposes.

Keywords: *drought, drought indices, precipitation, temperature*

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1. Introduction

Drought, marked by prolonged precipitation scarcity, is a natural disaster with widespread impacts. Economically, it harms agriculture, reducing crop yields, causing income loss for farmers, and disrupting supply chains, leading to short-term farmer unemployment. Environmentally, it distresses plant and animal life, elevates insect infestations and diseases, encourages erosion, and degrades habitats and landscapes. In severe cases, prolonged drought can trigger desertification due to persistent moisture scarcity. Socially, drought has profound consequences, resulting in water scarcity, unequal water distribution, disputes among users, uneven disaster relief distribution, and declining public health. Droughts occur in diverse climates, lasting from weeks to years. Factors such as rainfall onset, intensity, and duration, rainy day distribution, and current climatic conditions (temperature, wind, humidity) influence drought severity. Notably, drought is a temporary climate deviation, distinct from permanent aridity (Wilhite 1992). It can be mistaken for heatwaves, but droughts persist far longer (months to years), amplifying societal challenges when they coincide. Heatwaves typically last for about a week (Chang and Wallace 1987).

For effective drought management, acquiring data on its spatial extent, severity, and duration is essential. Drought indices serve as valuable tools for collecting this information, providing decision-makers with quantifiable insights into drought characteristics (Dogan et al. 2012). These indices are numerical metrics that gauge drought severity by amalgamating data from various factors such as evapotranspiration and precipitation. Unlike individual variables, using such an index is more user-friendly and encapsulates diverse environmental conditions. They serve as markers for arid environments and foretell agricultural and hydrological impacts, such as declining soil moisture or reservoir levels. The choice of data and technology for drought categorization can yield even more valuable insights. Incorporating remote-sensing imagery, for example, enables the assessment of vegetation health as a drought indicator, further enhancing the ability to understand and respond to drought events.

Over the years, many drought indices (more than 150) have been proposed for the characterization of droughts (Niemeyer 2008; Zargar et al. 2011; Hao 2012; Mukherjee et al. 2018). Some of the widely using indices are shown in Fig. 1 (Bhalme and Mooley 1980; Byun and Wilhite 1999; Gommes and Petrassi 1994; McKee et al. 1995; Narasimhan and Srinivasan 2005; Palmer 1965; Shafer and Dezman 1982; Tsakiris et al. 2007; Van Rooy 1965; Weghorst 1996; Wu et al. 2001). Each of these indices is a function of one or more hydro-meteorological parameters, including rainfall, temperature, evapotranspiration, groundwater, soil water, stream flow, etc. (World Meteorological Organization 1975; Zargar et al. 2011). Due to the intrinsic complexity of drought occurrences, each of these indicators has restrictions for application under different climatic conditions. Each has its own strengths and drawbacks. In the United States Palmer Drought Severity Index (PDSI)

(Palmer 1965) is mainly used while Rainfall Deciles based Drought Index (RDDI) (Gibbs and Maher, 1967) is common in Australia. The National Metrological Center in China extensively uses the China Z-Index (CZI) and Standardized Precipitation Index (SPI) (Edwards and McKee 1997) which is an internationally recognized index.

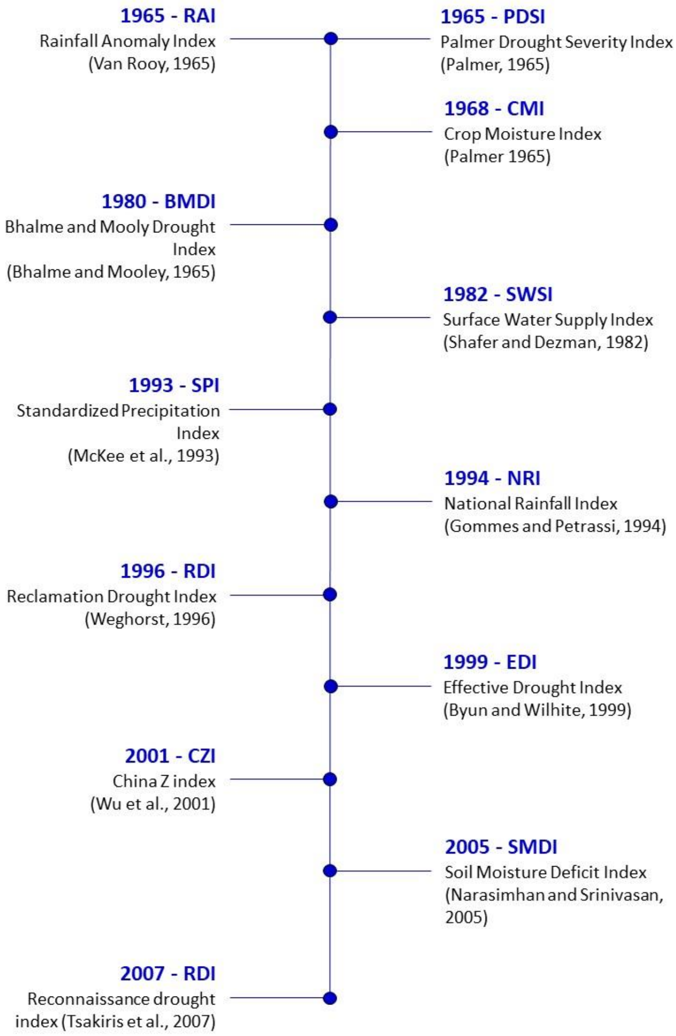

Figure 1: Development of some of the widely used drought indices.

In the past, numerous attempts have been made to determine whether different indices are suitable to describe the characteristics of drought in a particular area. Using data collected from 28 stations over a 40-years period (1960-2000), Loukas et al. (2008) calculated and compared three drought indices (Standardized Precipitation Index, Rainfall Anomaly Index, and China Z index) in Greece. The findings revealed that three indices performed similarly well in predicting the severity and duration of the drought. Raziei et al. (2007) also used SPI to evaluate the probability of drought persistence in Sistan and Balouchestan province, Iran, and discovered that drought persistence in central areas is greater than 70%, while it is less than 50% in eastern areas. Again, Lukas et al. (2008) assessed the climate change impact on the severity of drought in a large area of Tesla, Greece, using SPI and came to the conclusion that drought occurred with varying severity in all sections of this region at various times. The Spatial and Time Series Information Modeling (SPATSIM) software developed by Smakhtin and Hughes (2007) is used for the automated estimation of drought severity. In a drought research conducted in Orissa, India utilizing SPATSIM, Pandey et al. (2008) reported that EDI performed better than other indices. Analyzing 6 meteorological drought indices, Dogan et al. (2012) discovered that each identified drought characteristics differently.

Understanding drought phenomena is critical for planning and managing agricultural activities and water resources. In literature there were few comprehensive attempts to review drought concepts and drought indices (Mishra and Singh 2010; Zargar et al. 2011; Eslamian et al. 2017). However, over a decade, numerous new models and indices have emerged to address recent global drought occurrences. Therefore, this effort aims to refresh and expand the existing literature by incorporating these new developments and insights and aware academics and policymakers on commonly used drought indices in drought assessments.

The paper is structured as follows: the drought is briefly described in Section 1, the impacts of drought as a natural hazard are discussed in Section 2, and Section 3 defines and categorizes droughts. Section 4 begins with a classification of various drought indices, then moves on to major operational indices, other notable and recently introduced drought indices, and finally to the conclusion.

2. Drought's Effects as a Natural Hazard

A threat posed by naturally occurring phenomena that could endanger people, other creatures, or the environment is known as a natural hazard. Drought is a natural disaster that adversely affects agriculture, economy, and the quality of life for those who live in drought-stricken areas. Despite other common natural hazards such as earthquakes, floods, and tornadoes, drought has a lower mortality rate, but its effects are more widespread and last longer. Furthermore, among all natural catastrophes, it ranks top based on the total number of persons affected (Hewitt 1997; Wilhite 2000). According to Bryant's (1991) classification of hazardous occurrences based on their features and effects, drought is the most dangerous of all natural disasters. Earthquakes, tropical cyclones, regional floods and volcanoes come after drought in the list of natural disasters. Bryant (1991) ranked events according to their seriousness by taking into account their duration, total area affected, total number of fatalities, economic losses, social effects, long-term effects, suddenness, and occurrence of linked dangers. It is difficult to pinpoint a specific cause of drought because it is dependent on both atmospheric and hydrologic processes in the area that feed moisture into the atmosphere. Lower relative humidity results from less moisture loss through evapotranspiration from top soil layers when dry hydrologic conditions are established in a region. It is extremely difficult to reach saturation conditions under such conditions, which is required for the initiation of a rainfall. Hence, there is a less probability of having a rainfall. If sufficient moisture is delivered into the dry area via atmospheric turbulence, then drought can only be ended with sufficient rainfall (Bravar and Kavvas 1991).

Despite being considered a natural hazard, drought differs from other natural catastrophes in a number of ways (Wilhite 2000). Initially, it is challenging to pinpoint when a drought begins and ends because its effects build gradually and may last for a season, a year, or longer. Sometimes impacts may continue after the termination of the drought condition. Consequently, drought is known as a creeping phenomenon. Second, a universal definition could not be given for the drought since its impacts are complicated and interconnected. Third, consequences may have a wider geographic impact than potential harm from previous natural disasters. Drought rarely affects the structural alterations of water resource structures, unlike other severe natural disasters like floods, hurricanes, tornadoes, and earthquakes. As a result, it is much more difficult to quantify the impact and provide the necessary help than it is for other natural disasters (Wilhite 2000). Fourth, human actions like over-farming, deforestation, excessive use of surface and groundwater, and erosion can trigger a drought.

3. Definition and Classification of Drought

Drought is usually defined as extended periods with below-average rainfall causing a shortage of surface water, groundwater, or both (Oyounalsoud et al. 2023). It involves varying of hydro-meteorological variables and the stochastic behaviour of water demands in various geographical locations and different communities as well. Socioeconomic factors also aggravate the issue. Gonzalez and Valdés (2006) defined drought as the occurrence of a precipitation deficit across a certain area over a specific duration of time (Beran and Rodier 1985; Correia et al. 1991). The definitions have expanded to encompass effects on society and the environment in addition to time and place restrictions (Tsakiris and Vangelis 2005). Wilhite and Glantz (1987) emphasized that the conceptual and operational nature of a drought should also be considered in precise drought defining. While relative concepts like length and dryness have conceptual definitions, the operational definitions of a drought are its commencement, severity, and termination. Typical definitions of drought include: (i) 'a persistent, extended lack of precipitation' by the World Meteorological Organization (1986), (ii) 'According to the UN Convention to Combat Drought and Desertification, "a naturally occurring phenomenon that occurs when precipitation has been significantly below average recorded levels, generating serious hydrological imbalances that adversely affect systems for the development of land resources" (UN Secretariat General 1994), (iii) 'according to the Food and Agriculture Organization of the United Nations (1983), "the percentage of years when crops fail due to a lack of moisture", (iv) 'a protracted period of insufficient rainfall relative to the statistical multi-year mean for a location that may endure during a season, a year, or several years by the Encyclopedia of Weather and Climate (Schneider et al. 2011), (v) 'the smallest annual streamflow value' from Gumbel (Gumbel 1963), (vi) 'a considerable departure from the region's typical hydrologic conditions' from Palmer (1965), (vii) 'a continuous time without considerable rainfall' by Linseley et al. (1959). Depending on the parameter used to define a drought, definitions may change. Based on the definitions of drought Wilhite and Glantz (1985) have suggested four different forms of drought: (i) Meteorological drought, (ii) Hydrological drought, (iii) Agricultural drought, and (iv) Socio-economic drought.

3.1 Meteorological Drought

Meteorological drought can be defined by comparing the existence of precipitation in a particular area and at a particular time. It occurs when the region's actual precipitation is far lower than the region's climatological mean (Svoboda and Fuchs 2016). Therefore, drought is characterized by dryness resulted from precipitation deficit. Precipitation has typically been utilized in meteorological drought studies (Chang 1991; ELtahir 1992). Wu et al. (2004) defined the Meteorological drought as a deficit or any variation in the rain's intensity and velocity that raises the temperature, evapotranspiration, radiation, and the risk of hurricanes while reducing cloud cover and relative humidity. Therefore, meteorological parameters are the first indicators of drought occurrence. Monthly average precipitation and cumulative precipitation shortages have been used for drought intensity and duration analysis (Gibbs 1975; Chang and Kleopa 1991; Estrela et al. 2000).

3.2 Hydrological Drought

The levels of streams, lakes, and groundwater in water resource systems are used as hydrological indicators for defining a hydrological drought (Dutta et al. 2015). Accordingly, drought occurs when the levels of ground and surface water tables are lower than the long-term average. Severity of hydrological drought mainly depends on climatic fluctuations. However, human activities like shifting land uses, deteriorating the environment, and building dams make hydrological droughts more severe and frequent (Dutta et al. 2015). Hydrological droughts are increasingly common today due to the increased urbanization, industrialization, and water use. For hydrologic drought studies, streamflow data are frequently used (Clausen and Pearson 1995; Mohan and Rangacharya 1991).

3.3 Agricultural Drought

Agricultural drought happens when the soil moisture content is below the water requirement of plants. Due to reduced precipitation, the soil moisture content is gradually decreased and the plant exposes to a tension so that crop failures occur leading to a yield reduction. There is no connection between these phenomena and surface water resources. A number of factors, including a lack of precipitation, an increase in temperature, and wind contribute to a decrease in soil moisture, but the volume and timing of the precipitation have the most impact. Crop water requirements vary depending on the type of plant, growth stage, soil characteristics such as physical and biological; hence, the concept of agricultural drought also varies. According to Webster (1978), agricultural drought happens prior to a hydrological drought and following a meteorological drought.

3.4 Socio-Economic Drought

When water resources are insufficient to meet the demands of industry, agriculture, and home consumption, socioeconomic anomalies result, and thus socioeconomic droughts occur. This type of drought is resulted from a complex environmental process and causes to series of negative impacts on human communities such as poverty, unemployment, outbreaking of diseases etc. Social insecurity conditions are happened due to impacts over the economic activities such as reduction of revenue from sales and mismatch between supply and demand of water, food, grains, and fish. Further, the reduction of the hydroelectric energy supply is greatly affected for socio-economic activities.

4. Drought Indices

A drought index is an important tool used to assess the impact of a drought and determine its aspects, that include duration, intensity, geographic extent and severity. The World Meteorological Organization (1986) defines the drought index as a measure of some of the cumulative effects of prolonged and abnormal moisture deprivation. The drought variables need to be measured the drought on several time scales, such as annually, seasonally monthly, etc. However, a year is the most frequently used time period for drought studies. It may elaborate the regional behavior of droughts. To measure the consequences of droughts on agriculture, water supply, and groundwater regime, it is important to analyze droughts monthly (Panu and Sharma 2002). The following purposes could be served by using drought indices:

- *Real-time monitoring and drought detection (Niemeyer 2008)*
- *Determine the onset and termination of a drought of drought event (Tsakiris et al. 2007)*
- *Evaluation of a drought (Niemeyer 2008)*
- *Detect the level of drought and urge drought response measures*
- *Recognize the sense of drought in a specific area (Tsakiris et al. 2007)*
- *Facilitate to communicate among various interested parties on the drought condition*
- *Assess the quantitative effects of drought at various geographic and temporal scales*

4.1 Taxonomy of drought indices

Based on the impacts of drought, type of data used (Niemeyer 2008) and variables embedded in (Steinemann et al. 2005) drought indices are classified. Accordingly, three common types; hydrological, meteorological and agricultural drought indices are popular among the scientific community of the world. However, Niemeyer (2008) added three more types as; combined, remote-sensing based and comprehensive, considering the complexity of the above three categories.

4.1.1 Meteorological Drought Indices

At the initial stage drought indices have been developed by using observed meteorological parameters at meteorological stations. There were several indices which used precipitation as the basis for the index calculation (Table 1). A meteorological drought, on the other hand, is caused not only by a lack of precipitation but also by temperature, which impacts evapotranspiration. Therefore, evapotranspiration has been incorporated to better correlate the drought impacts of temporal trends in temperature. Some examples for precipitation and evapotranspiration driven indices are shown in Table 1.

4.1.2 Hydrological Drought Indices

It was aimed to characterize the hydrologic impacts of drought by this group of indices. In-depth analyses of streamflow data from gauging stations, such as recession analysis or flow duration curves, are displayed in low flow indices like Q90 or the Base Flow Index.

Table 1: Precipitation and evapotranspiration-based drought indices.

Precipitation driven indices		Evapotranspiration driven indices	
Indices	**Reference**	**Indices**	**Reference**
Rainfall Anomaly Index - RAI	Van Rooy 1965	Standardized Precipitation Index - SPI	McKee et al. 1993
Bhalme and Mooly Drought Index - BMDI	Bhalme and Mooley 1980	Reconnaissance Drought Index - RDI	Tsakiris and Vangelis 2005
Drought Severity Index - DSI	Bryant et al. 1992	Standardized Precipitation Evapotranspiration Index - SPEI	Vicente-Serrano et al. 2010
National Rainfall Index - NRI	Gommes and Petrassi 1994		
Effective Drought Index - EDI	Byun and White 1999		
Drought Frequency Index - DFI	González and Valdés 2006		

The first attempt at this category was the Palmer Hydrological Drought Index (PHDI) (Palmer 1965), which employed soil moisture, runoff, evapotranspiration, and precipitation to measure drought. By incorporating hydrological factors such as reservoir storage, snowpack, and runoff into Palmer Drought Severity Index (PDSI), Shafer and Dazaman (1982) established the Surface Water Supply Index (SWSI), which was the most well-known of this category. By incorporating temperature into SWSI to determine variable water demand,Weghorst (1996) has developed Reclamation Drought Index (RDI). Water Balanced Derived Drought Index (WBDDI) (Vasiliades et al. 2011), Regional Stream Flow Deficiency Index (RSDI) (Stahl, 2001) and Groundwater Resource Index (GRI) (Mendicino et al. 2008) are some of the examples in this group.

4.1.3 Agricultural Drought Indices

The agricultural drought indices mainly evaluate soil water balance and associated shortfall in soil moisture content in a drought situation. By using weekly soil moisture, soil moisture deficit is calculated. The length of the drought is then taken into consideration by gradually adding weekly values. By merely considering the moisture deficit in the top layer of soil, Relative Soil Moisture (RSM) (Thornthwaite and Mather 1955) and Crop Moisture Index (CMI) (Palmer 1968) simulate short-term agricultural droughts. Crop Specific Drought Index (CSDI) (Meyer et al. 1993) which is based on Corn Drought Index (CDI) (Meyer et al. 1993) and Soybean Drought Index (SDI) (Meyer and Hubbard 1995), estimates soil water availability at various zones and layers. Soil moisture deficit could be calculated for various soil layers and depths for finer resolution using the Soil Moisture Deficit Index (SMDI) and Evapotranspiration Deficit Index (ETDI) (Narasimhan and Srinivasan 2005). SMDI considers soil moisture content and EDTI considers the water stress ratio. With the help of a water balance model and crop transpiration, Matera et al. (2007) developed Agricultural Drought Index (DTx) to assess the transpiration deficit over a period of time.

4.1.4 Comprehensive Drought Indices

Various meteorological, hydrological and agricultural variables are embedded in comprehensive indices to visualize the comprehensive nature of a drought. An example of this category is the Palmer Drought Severity Index (PDSI) (Palmer 1965). To describe the drought, the existing water content of the soil has also been added as an additional variable.

4.1.5 Combined Drought Indices

It is also known as a hybrid drought index or an aggregate drought index. These are created by combining two or more already-existing drought indices into a single index in order to take full advantage of the information that is easily accessible and has been shown to be appropriate in specific drought indices. Examples of this category include the Aggregate Drought Index (ADI) (Keyantash and Dracup 2004)), US Drought Monitor (USDM) (Svoboda et al. 2002), Vegetation Drought Response Index (VegDRI) (Brown et al. 2008), and Hybrid Drought Index (HDI) (Karamouz et al. 2009).

4.1.6 Remote-sensing based Drought Indices

An innovative avenue for drought monitoring and detection opened up with the creation of earth observation satellites from the 1980s onward equipped with sensor technologies. Remote sensing data are used in these indices to track the status of the land's surface, particularly its vegetation. The majority of drought indices developed after the 1980s were remote-sensing based. Some well-known indices in this category include the Normalized Difference Vegetation Index (NDVI) (Tucker 1979), the Water Supplying Vegetation Index (WSVI) (Chen et al. 1994), the Standardized Vegetation Index (SVI) (Peters et al. 2002), the Cumulative Water Balance Index (CWBI) (Dennison et al. 2003), the Total Storage Deficit Index (TSDI) (Yirdaw et al. 2008), and the Vegetation Water Supply Index (VWSI) (Cai et al. 2010).

4.2 Key operational drought indices

Commonly used drought indices are discussed along with their benefits, drawbacks, and comparisons to other indices in this section.

4.2.1 Standardized precipitation index (SPI)

SPI is a widely used drought monitoring method/ tool for selected time frames (McKee et al. 1993). The primary input variable of SPI is long-term precipitation data. First, precipitation records are fitted into gamma probability distribution function and converted to normal distribution through equal-probability transformation. The transformed SPI values range from -2.0 to +2.0. The zero of this scale represents the mean SPI for the particular location and desired time period. Values above zero denote wet seasons, whereas those below denote dry seasons. Excessive deviations from this range occur only 5% of the time, according to Edwards and Mckee (1997). By transforming precipitation records into a normal distribution, SPI overcomes the discrepancies occurring due to use of non-standardized precipitation records. The ability to calculate drought levels for different time steps including 3, 6, 12, 24 and 36 months is a prominent advantage of this method. This flexibility enables the monitoring of both long-term changes in water resource structures like lake and reservoir levels, streamflow levels and groundwater supplies as well as short-term water deficiencies like soil moisture (Mishra and Singh 2010). The main shortcomings of this method are that SPI can only be used to calculate the precipitation shortage and values fluctuate as the time of record increases.

4.2.2 Palmer drought severity index (PDSI)

Based on meteorological parameters such as precipitation, temperature and locally available water content, Palmer (1965) has developed the PDSI and even today it is extensively used for drought monitoring. It is possible to compute evapotranspiration, moisture, runoff and soil recharge in the monthly time scale of the water balance equation from PDSI. It records as the first systematic attempt to determine the entire moisture regime of a region. PDSI is suitable for relatively homogeneous locations and includes a soil moisture algorithm. Instead of a short-term (weekly scale), this indicator is employed on a monthly time scale and is an efficient means of determining long term drought (Wu et al. 2004). Fig. 2 shows various drought classes based on Palmer index. In the past, several modified versions have been introduced by changing their original form. Karl (Karl 1986) changed the original version of PDSI as Palmer Hydrological drought index for water supply monitoring and Heddinghaus and Sahol (1991) revised PDSI as Modified PDSI for real time operational purposes.

One of the most popular and reliable drought monitoring systems is PDSI. It has been used by Palmer (1967) and Karl and Quayle (1981) to demonstrate the spatial distribution and severity of various drought events. PDSI has been utilized by certain academics to investigate the regional and temporal aspects of droughts (Diaz 1983; Jones et al. 1996; Karl and Koscielny 1982; Soulé 1992). Further, it has been used to investigate the recurring patterns of droughts (Rao and Padmanabhan 1984), track hydrologic changes, predict crops, and estimating the probable severity of fire (Heddinghaus and Sahol 1991), analyse widespread droughts (Johnson and Kohne, 1993), and predict droughts (Kim and Valdés 2003; Özger et al. 2009).

Alley (1984) discussed two distinct advantages of PDSI: (1) It strengthens the planners' capacity for judgment in assessing and quantifying climate abnormalities in a region, (2) PDSI provides an overview of past droughts in terms of time and space.

PDSI does, however, have a number of drawbacks. These drawbacks have been described by Alley (1984) and Karl and Knight (1985) as, (1) Due to its monthly time span, PDSI is considered suitable for agricultural drought than hydrological drought. (2) this index treats all precipitation as rain and ignores snowfall, snowpack, and frozen ground (3) slow reaction times for emerging and warning droughts (Hayes et al. 1999).

4.2.3 Crop Moisture Index (CMI)

Based on weekly mean temperatures and precipitation, Palmer (1968) created the Crop Moisture Index (CMI) to investigate the short-term moisture budget (week to week) for agricultural areas. Final CMI values are calculated by modifying empirical relationships and comparing variables from moisture budget computations to long-term average values. It is computed with consideration for both time and space. CMI shows weekly general conditions of the region so that most suited for rapidly changing conditions. CMI is not an appropriate instrument to study long-term drought features since it provides effective moisture conditions for growing crops in the short term. This index may provide misleading information about long-term circumstances because of its sensitivity to short-term variations in precipitation and temperature. For instance, an increase in CMI values suggests higher moisture levels, yet there is never a situation when dry conditions are present. Due to this restriction, CMI cannot display moisture conditions outside of the season, especially in cases where droughts are long-lasting. However, CMI are very effective in evaluating short term agricultural droughts in warm seasons (Heim 2002).

4.2.4 Surface Water Supply Index (SWSI)

In response to the limitations of the PDSI for mountain snow hydrology, Shafer and Dezman (1982) designed the SWSI. It was initially developed as a hydrological drought measure to track irregularities in sources of surface water supply. SWSI uses monthly timescales and its primary inputs are past records of reservoir storage, streamflow, snowfall, and precipitation (Raziei et al. 2007). It was created specifically for Colorado, where the region is covered with significant snowpack and is thought to be the main source of surface water supply. It eliminates the limitations of Palmer index which cannot be used in high topographic diversity. The main aim of Shafer and Dezman (1982) was to combine climatic and hydrologic characteristics into a single index that is appropriate for assessing how hydrologic droughts affect urban and industrial water supplies, agriculture, and power generation. SWSI is depending on the season of the year in which precipitation, snowfall and reservoir storage are used throughout the winter months. In summer, streamflow replaces the snowpack. Spatial and temporal variation due to different watersheds and seasons, and different statistical properties could be observed in SWSI index. That is the main limitation of SWSI.

4.2.5 Effective Precipitation Index (EPI)

Using daily effective precipitation values as inputs, Byun and Wilhite (1999) designed EPI as a time-dependent reduction function. Daily interval is the time scale of this function and it can be effectively used for estimating drought duration, monitoring prevailing droughts, and defining a variety of drought characteristics. Three additional indices are embedded in EPI which are (1) daily mean effective precipitation (MEP) (2) deviation of effective precipitation (DEP) from MEP and (3) standardized value of DEP (SEP) (Byun and Wilhite 1999). The commencement, retreat and duration of drought events can be categorized by using these three indices. EPI can be used to characterize both hydrological and meteorological droughts so that researchers can look into the drought situation at any time and demonstrate how it has affected soil and water resources.

4.2.6 China Z- Index (CZI)

The National Climatic Center (NCC) of China created the CZI, which is currently widely used in China to track the status of droughts (Wu et al. 2001; Dogan et al. 2012). Since it uses monthly precipitation as the input parameter to determine wet and dry periods over multiple time scales, it is similar to SPI. The Wilson-Hilferty cube-root transformation (Wilson and Hilferty 1931) from the chi-square variable to the Z-scale is connected to CZI, which presupposes that precipitation records perform the Pearson Type III distribution (Kendall and Stuart 1977). It allows for the detection of droughts of varied lengths by using monthly time steps ranging from 1 to 72 months. Z score is the statistical Z value that can be computed for time step 't'. However, NCC only calculates CZI for one-month time step. Major strengths of CZI include simple calculation, computing for several time steps, use in wet and dry events and allowing missing data. The main drawback of CZI is that shorter time scales may be underrepresented compared to SPI because the data for Z-score do not need to be adjusted by fitting them into gamma or Pearson type II distributions.

4.2.7 Rainfall Departure (RD)

Another reliable measure of an area's current dry or wet conditions is rainfall departure (RD). When calculating RD, long term mean is subtracted from the monthly rainfall and then divided by the long-term average. It includes simple calculations and is straightforward to understand. It can be computed using seasonal or monthly time steps. Excess rainfall is represented by positive values and deficit is represented by negative values. RD is used for weather prediction and is suitable for defining shorter-term local weather conditions. Wet or dry conditions are defined according to local situations. For instance, a year is classified as drought by the Indian Meteorological Department if the annual rainfall is less than 75% of the long-term average (Rao 1986), whereas in South Africa, a drought year is defined as one with less than 70% of the year's average rainfall (Smakhtin and Hughes 2004).

4.2.8 Effective Drought Index (EDI)

Using the concept of effective precipitation, Byun and Wilhite (1999) introduced the Effective Drought Index (EDI), which tracks the duration and severity of drought. In EDI, the effective precipitation is estimated as a function of the current month's rainfall and weighted rainfall over a specified prior period using a time-dependent reduction function. The quantity of precipitation required to return to normal (PRN) is utilized in the computation of EDI. The precipitation required to return to normal is calculated using monthly effective precipitation and deviation from the mean.

Initially, EDI was created to track the status of the drought on daily basis (Akhtari et al. 2009; Kalamaras et al. 2010; Lee et al. 2012). It was then expanded to include tracking monthly drought conditions (Deo and Byun 2014; Pandey et al. 2008). EDI and SPI follow the same drought severity classification. A time-dependent reduction function is used to determine the daily or monthly effective precipitation, and a minimum of 30 years of data is required. The time step should be defined as monthly for calculating the monthly EDI. The current month's rainfall should be given more weight, and the preceding months' rainfall should be given weights in decreasing order. The reduction function of EDI allows for a precise definition of the beginning and ending dates of the drought.

4.2.9 Soil Moisture Deficit Index (SMDI) and Evapotranspiration Deficit Index (ETDI)

Narasimhan and Srinivasan (2005) developed the SMDI and ETDI by taking into account the geographical diversity of hydrological properties of soil type and land cover, as well as meteorological indicators for agricultural drought monitoring. The SMDI and ETDI are calculated using the weekly soil moisture deficit and evapotranspiration deficit, respectively. A high spatial (16 km^2) and temporal (weekly) resolution of hydrologic model is used with a crop growth model in this computation. For various soil layers and depths, weekly values are computed. Weekly values give an accurate picture of recent dry conditions, which is especially useful when a plant is growing. In

SMDI and ETDI, the hydrologic system is better modelled, and a finer resolution of soil moisture deficit monitoring is achievable. Therefore, it may be possible to enhance older indexes like the SPI, PDSI, and SWSI by this.

4.2.10 Reconnaissance Drought Index (RDI)

RDI is a recently developed (Tsakiris and Vangelis 2005) drought index which is more comprehensive than SPI. Since precipitation alone does not provide a true estimate of moisture deficit and the severity of drought, both precipitation and potential evapotranspiration (PET) have been taken into consideration in its creation. They have identified the difficulty of correlating the damage from the drought when PET is omitted from the equation. Prominent advantages of RDI include: RDI determines the total deficit between precipitation and the atmosphere's evaporative requirement; being adaptable throughout a range of time; better affiliation with agricultural and hydrological droughts; Utilizing monthly precipitation and PET, RDI may also be calculated quickly and easily.

4.3 Other notable drought indices

In addition to the above-mentioned drought indices, there are some other notable drought indices which have been used for drought evaluation and monitoring in the past. Table 2 summarizes some of those prominent drought indices.

4.4 Recent drought indices

During the previous two decades, a number of drought indices have been formulated to avoid the limitations of earlier drought indices. Table 3 provides a summary of some of those.

5. Conclusions

All the indices developed to characterize droughts use single or multiple meteorological and hydrological parameters. Though it makes more complex when the number of parameters is increased, it gives a more realistic picture of the drought condition of the region. The index chosen and the hydro-meteorological data that are available determine how well a drought episode can be described. A suitable index might be chosen from the extensive selection of meteorological, hydrological, comprehensive, integrated, and remote sensing-based drought indices in accordance with the characterization requirement. The most limiting factor in selecting a suitable index is the unavailability of long-term hydro-meteorological information. During the last two-three decades, most countries around the world have experienced frequent as well as severe droughts. This scenario is aggravated by growing water demand and climate changes all around the globe. To mitigate the consequences of drought on human life, agricultural, and socioeconomic difficulties, it is crucial to identify drought features early. The role of all water resource planners or decision makers is to analyze the historical, present and future effects of droughts and take necessary actions to mitigate the impacts. Although numerous drought indices are available for specific needs and specific regions, still there is a huge gap to be satisfied.

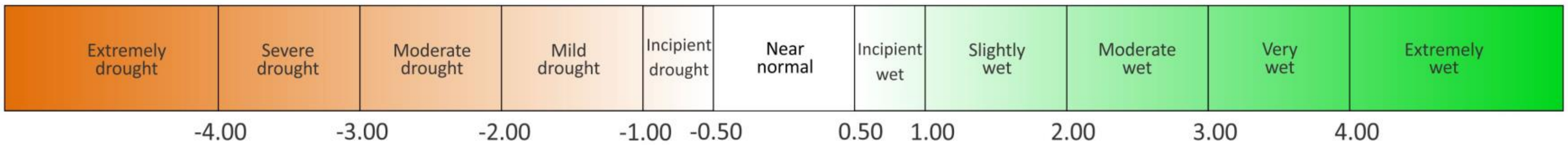

Figure 2: Classes of Palmer drought index

Table 2: Other notable drought indices.

Drought index	Reference	Category	Inputs				Remarks
			P	T	SF	Other	
Z-index	Palmer 1965	M	X	X	X	ET, SM	Measures short term drought on a monthly scale, can use to compare current drought with known other, it can also use to determine end of a drought period.
Palmer Modified Drought Index (PMDI)	Palmer 1965	M	X	X	X	ET, SM	The primary distinction is in how rapidly it reacts compared to PHDI when calculating the start and end of dry and wet periods.
Palmer Hydrological Drought Index (PHDI)	Palmer 1965	H	X	X	X	ET, SM	Compares drought patterns based on meteorology and hydrology over both space and time, Its water balance approach allows the total water system to be considered.
Keetch-Byram Drought Index (KBDI)	Keetch and Byram 1968	M	X	X			Calculate the amount of water needed to restore the soil to its ideal moisture level and the soil moisture deficit. It is widely using in predicting and controlling forest fires.
Crop Water Stress Index (CWSI)	Idso et al. 1981; Jackson et al. 1981	RS				RS	Canopy thermal images are used for crop water stress monitoring.
Normalized Difference Infrared Index (NDII)	Hardisky et al. 1983	RS				SWIR, NIR	This was used to track vegetation water content and is closely connected to leaf and canopy water content.
Vegetation Condition	Kogan 1990	RS				NVDI	It contrasts the range of values for the present

Index (VCI)							Normalized Difference Vegetation Index (NDVI) with those for the comparable time in prior years. It expresses in % and higher and lower values indicate good and bad vegetation conditions, respectively.
Crop Specific Drought Index (CSDI)	Meyer et al. 1993	A	X			WS, SR	Used to determine how drought affects crop yields. Very specific to the type of crop, Ex. Corn drought index (CDI, Meyer et al. 1993), Soya bean drought index (SDI, Meyer and Hubbard, 1995)
Reclamation Drought Index (RDI)	Weghorst 1996	H	X	X	X	SP, ReS	It can be used to gauge the intensity and length of a drought as well as to foretell its beginning and end. Calculate at the drainage basin level and has both dry and wet scales
Effective Drought Index (EDI)	Byun and Wilhite 1999	M	X				Single input required index which can be used for any location in the world and results standardized for comparisons. Gives a clear definition on the onset, ending and duration of drought.

Where, A is Agricultural, BT is brightness temperature, ET is evapotranspiration, EV is Evaporation, H is Hydrological, M is Meteorological, NIR is Near-Infrared, P is precipitation, ReS is reservoir storage, RS is remote sensing, SF is streamflow/runoff, SP is snowpack, SR is solar radiation, SWIR is Short Wave Infrared, T is temperature, SM is soil moisture, VWC is Vegetation Water Content and WS is wind speed.

Table 3: Recently developed drought indices.

Drought index	**Reference**	**Type**	**Inputs**				**Remarks**
			P	T	SF	Other	
Vegetation Temperature Condition Index (VTCI)	Wang et al. 2001	RS					Can be used to track the occurrence of droughts at the regional level for a predetermined amount of time (10 days, for example). Additionally applicable for studying the geographic distribution of drought.
Regional Streamflow Deficiency Index (RSDI)	Stahl 2001	H			X		Uses flow duration curves. Cluster analysis is used to find homogenous areas.
Aggregate Drought Index (ADI)	Keyantash and Dracup 2004	A	X		X	ReS, SM, SP	An aggregate drought index which can be used to describe, hydrological, meteorological and agricultural droughts.
Reconnaissance Drought Index (RDI)	Tsakiris and Vangelis 2005	M	X			PET	The ratio of potential evapotranspiration to cumulative precipitation for a given period is the fundamental form of RDI. RDI is better suited for assessing the effects of drought on agriculture because it takes into account both the primary input and output of natural water systems. Further, estimation of RDI is simple and easy.
Modified Perpendicular Drought Index (MPDI)	Ghulam et al. 2007	RS					Vegetation fractions has been added to earlier developed Perpendicular Drought Index (Ghulam et al. 2007b) to minimize the effect of surface variation (due to bare soil and vegetation).
Normalized Multi-Band Drought Index (NMDI)	Wang and Qu 2007	RS					Two liquid-water absorption bands (1640 and 2130 nm) in the shortwave infrared range are used to assess the water sensitivity of vegetation.
Vegetation Drought Response Index (VegDRI)	Brown et al. 2008	A					Utilize satellite-based measurements of the state of the vegetation, information on the climate, and other biophysical data (soil properties, ecological environment, and land

					cover/land usage type)
Hybrid Drought Index, (HDI)	Karamouz et al. 2009	A			SPI, SWSI, and PDSI combined
Standardized Precipitation Evapotranspiration Index (SPEI)	Vicente-Serrano et al. 2010	M	X	PET	An extension of widely used SPI. SPEI, in contrast to SPI, accurately measures the primary effect of rising temperatures on water demand. If limited data is available (P and T), PET could estimate by simple Thronthwaite method. If more data is available (wind speed surface humidity, solar radiation etc.), more sophisticated method can be used.
Modified Reconnaissance Drought Index (RDIe)	Dimitris, D. et al. 2016	M	X	PET	Precipitation of RDI is replaced by effective precipitation. It is possible to describe the amount of water that agricultural systems use to their advantage more accurately.

where A is Agricultural, ET is evapotranspiration, H is Hydrological, M is Meteorological, P is precipitation, PET is potential evapotranspiration, RS is remote sensing, ReS is reservoir storage, SF is streamflow/runoff, SM is soil moisture, SP is snowpack and T is temperature.

Following general limitations can be identified by reviewing most of the literature on drought indices and their applications.

1. *There is no universally accepted index to characterize all droughts all over the globe.*
2. *Drought indices can only reflect drought conditions such as onset, end, duration and severity. However, any index may not suit to quantify the economic losses due to droughts.*
3. *Drought indices consider the precipitations as a dominant parameter in defining drought characteristics, however, the demand for water is not considered. If the demand for water is higher, droughts may arise quicker than where the demand is less.*
4. *The heterogeneity of soil properties may cause to produce poor definitions when incorporating soil moisture as a parameter in drought indices.*
5. *Probably, unpredictable climate changes lead to misinterpretation of drought characteristics.*

Therefore, a big opportunity is available to revisit all developed drought indices or explore newer indices for catering above limitations. However, as used by many researchers and authors all over the world in the past, substantial characterization could be done by using SPI, PDSI, CMI, SWSI, EPI, CZI, RD, EDI, EDTI, RDI, etc.

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