Drought indices: aggregation is necessary or it is only the researcher’s choice

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ABSTRACT

Drought is a natural phenomenon caused by extreme and persistent precipitation shortage. This shortfall causes impacts on hydrology, agriculture, and the economy of a country. Secondly, drought/dryness has certain unique characteristics (severity, duration) among the natural hazards which makes it difficult to classify the persistent and subjective network of impacts. Drought classification is important to manage drought, allowing both quantitative evaluation and potential risk assessment planning. The simpler approach of drought indices made it easier for various researchers and organizations to classify drought. Several drought indices have been proposed at the national and global level to characterize hydrological, meteorological and agricultural droughts. Until now, there has been no widely agreed drought index among researchers. Therefore, researchers are trying to modify and reconstruct a simple, complete, and robust drought index for effective use and planning of the management of water resources. Due to the complex terrestrial ecosystem, researchers used to integrate multiple drought indexes for evaluation and monitoring of regional drought conditions. The reviewed composite or aggregated indices revealed that the researchers are mainly focused on regional climatic and environmental conditions, and differences of theoretical backgrounds while integrating a drought index. There is a lack of performance evaluation of these indices because usually the comparative analysis between the integrated index and earlier developed composite indices is not performed. Secondly, the developer researchers did not mention limitations such as data, which is considered a paramount issue while applying these indices in other regions. Therefore, there is still comprehensive work needed for the simple integration of drought indexes for general applications.

Key words: climate change, composite index, drought climatology, drought, evapotranspiration

HIGHLIGHTS

• Integrated drought indices are selected to study the limitations in indices.
• Complex terrestrial ecosystem, researchers used to integrate multiple drought indexes.
• Integrated drought indices are lacking in performance evaluation.

GLOSSARY

PDSI Palmer Drought Severity Index
FIDI Fuzzy Integrated Drought Index
EAPI Evapotranspiration Anomaly Percentage Index
PAPI Precipitation Anomaly percentage index
SMAI Soil Moisture Anomaly Percentage index
RAI Runoff Anomaly Percentage Index
SPI Standardized Precipitation Index
SPEI Standardized Precipitation Evapotranspiration Index
SWSI Surface Water Supply Index
WMO World Meteorological Organization
MDIs Meteorological Drought Indices
Z-index Z index palmer
RAI Rainfall Anomaly Index
KBDI Keetch-Byram Drought Index
PMDI Palmer Modified Drought Index

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INTRODUCTION

Drought occurrence has become very frequent globally (Dai 2011; Trenberth et al. 2014). Although there are tangible debates on the perspectives and definitions of drought, there exists no accepted global standard explanation. Briefly, drought can be defined as a deficiency or shortfall of precipitation by an estimated mean within a period over a region (Dracup et al. 1980; Correia et al. 1991; González & Valdés 2006; Mishra & Singh 2010, 2011; Azmi et al. 2016). Therefore, the impacts expressed by drought are essential in realizing the context of drought. In literature, several drought realizations were identified by (Wilhite & Glantz 1985).

From the research, four major types of drought such as meteorological, agricultural, hydrological, and socio-economic droughts are classified (Figure 1). Meteorological and hydrological droughts are linked with a reduction in precipitation. In these droughts, meteorological droughts have purely occurred when there is a precipitation reduction while hydrological droughts have happened when runoff or streamflow is declined due to less precipitation or other human activities like in the upstream built-up of hydrological structures. Likewise, agricultural droughts have occurred when there is a deficit of soil moisture while socioeconomic droughts were the result of ecological water deficit or human water use (Huang et al. 2016; Faiz et al. 2018b, 2020; Mukherjee et al. 2018; Yihdego et al. 2019).

The above mentioned all types of drought begin as a result of a deficiency in precipitation over a period of time or space. Early stages of drought start as a result of an accumulation of a deficiency in precipitation, which is commonly known as meteorological drought. Deficiency in precipitation is caused by the persistence of high temperatures above normal, high winds, and relatively low humidity over time. Therefore, there are great environmental and socioeconomic impacts as a result of drought. Different regions have different patterns concerning the climatic conditions; thus, meteorological droughts are stated as a change in the hydro-meteorological and local geographical conditions. Hence, meteorological drought is mainly defined by the difference in the geographical, hydro-meteorological, and climatological conditions. There is a high possibility of the rapid development of meteorological drought, although this drought can end up easily if the precipitation deficits are small. Meteorological droughts can also stay longer than usual or can develop into other drought types. For example, meteorological drought can also develop into agricultural drought in this case, if there are precipitation deficits during the crop growing season resulting in the restrained growth and development of plants (Narasimhan & Srinivasan 2005; Eslamian 2014). Therefore, agricultural drought can be regarded as the next phase resulting from meteorological droughts. Agricultural drought, therefore, refers to a drought whereby
there is an extension of its characteristics for a while, leading to the effects of a region's agricultural demand as a result of lack of soil moisture. Agricultural drought has the potential to extend beyond the growing seasons, but there may exist a natural break between seasons in case no agricultural activities were taking place. There are also instances whereby agricultural drought precedes a growing season in case the situations do not favor planting.

Hydrological droughts are events of droughts that result in the reduction of water availability in the water resources (Eslamian 2014). Meteorological droughts may last for longer periods leading to a lack of surface flow due to soil dryness, thereby affecting the hydrological situation of a certain region. It is hard to monitor the hydrological impacts of drought in a certain region just after initiation. Therefore, an extension of the dry period in a certain region could result in a decline in the streamflow, soil moisture, or subsurface recharge. During the winter season, the frozen precipitation is for future runoff, while in the case of a dry winter, there may be an emergence of hydrological drought in the preceding months. Despite the existence of precipitation events, dry soil is a great inhibitor of substantial runoff. Also, dryness and heat can lead to a reduction in the availability of water in a hydrological system. Water can be withheld by water managers in some hydrological systems in case there is a concern of hydrologic drought to assist in moderating its future impacts. Although the precipitation may return to normal, the hydrology of a region may be affected by long-term hydrological drought.

The socioeconomic meanings of drought definition may differ from the other types of drought as the occurrence of this drought is dependent on the process of economic goods and supply and demand which are related to agricultural and meteorological elements (Wilhite & Glantz 1985; Arab et al. 2010; Shi et al. 2018; Guo et al. 2019). Climate and weather conditions can be used to explain the scarcity of certain goods and to describe why the demand for certain goods exceeds their supplies. Development of the socioeconomic drought impacts may be observed immediately in a region and can extend over time depending on the severity and impacted of the value of the good. Likewise, the ecological drought is referred to as a prolonged deficiency in the availability of natural water supplies either in natural or managed hydrology. For example, ecological drought

![Figure 1](https://iwaponline.com/ws/article-pdf/doi/10.2166/ws.2021.163/895014/ws2021163.pdf)
may affect the ecological water level (the lowest level of water required for the natural functioning of an ecosystem in a lake) of a certain lake (Wantzen et al. 2008; Liu et al. 2012; Crausbay et al. 2017).

Drought characteristics and monitoring

Due to the hardships in the existing definition of drought, their development is dependent on the indicators or indices which help in determining this phenomenon. Therefore, to study drought, primary information on the characteristics of weather and climate in a specific region must be first gathered to define the probability of a past or an ongoing drought event. A regular regional climatological behavior may be a sign of drought initiation in another region. Proper planning may be a possibility of mitigating the impacts of probable drought in this case if it is assumed that a unique dry pattern exists in the region. Monitoring the drought conditions may be conducted by early warning systems that might be helpful for adequate preparation of any drought event (Liu & Kogan 1996; Wilhite & Svoboda 2000; Paulo et al. 2005; Heim & Brewer 2012; Wilhite 2016). Adequate preparation is critical to mitigating the drought consequences, which may lead to worse outcomes in the region.

Reliable and long-term precipitation data is very critical for basic drought characteristics. Some fundamental drought characteristics such as timing, duration, severity, magnitude, intensity, frequency, and predictability are defined and used by (Yevjevich 1967; Dracup et al. 1980; Salas 1993). For example, the duration of drought depends upon its dynamic nature which maybe for a week or year. The accumulated water deficit in the form of runoff, soil moisture, and precipitation below the defining threshold during the drought period is called the magnitude. Similarly, the ratio of magnitude and duration is defined as drought intensity, and severity is related to precipitation deficit degree. Based on these characteristics, the drought early warning systems are developed through the comparisons of the archives with the current weather events. Precipitation is known to be the cornerstone indicator of many droughts, but other indicators are critical in assessing the severity of the drought. In a study area, one should ideally monitor rivers and streams, storage of water, moisture in the soil and crop production, in addition to any other indicator that is perilous in understanding the availability of water. The quality and quantity of information available in many regions do not warrant a determination of whether the region is ravaged by drought because it may not be possible to assess each indicator. However, in verifying the existence of drought severity, multiple indicators should be evaluated. For accurate analysis of the current and historical conditions, reliable and longest gap-free records are vital. Drought should be understood as a feature category whereby a region’s dry side is expressed in temporal and spatial existence of precipitation. For an accurate statistical definition, extreme events are better understood if they fall within a sample size. A previous study documented that at least fifty years of precipitation record should be available for accurate definition and analysis of seasonal and long-term drought periods (Guttman 1999). For example, if we use the standardized precipitation index (SPI), then more data is vital when drought covers multiple years. On the other hand, some indicators which are associated with remote sensing data may not have long records. For proper monitoring of drought, enough time and energy should be dedicated to reconstructing and developing datasets that have many points. Nevertheless, the loss of information during the reconstruction of data is an issue that should be taken care of while the development of data. Upon completion of the research, tracking conditions not only adds to the recording period but also enables scientists and researchers to gain near insight into the environment and climate in the area. Therefore, it is critical to understand the monitoring of current conditions to know about the amount of precipitation that is expected over a period. Besides, the beginning of a drought cannot be necessarily characterized by a precipitation decrease for a typical seasonal precipitation duration of a region. Therefore, the determination of precipitation is vital for any area.

Indicators/indices

An indicator is defined as a scale variable in the hydrological, meteorological, socioeconomic, and agricultural related studies indicating a deficiency or a drought-related potential (Svoboda & Fuchs 2016; Eslamian et al. 2017). On the other hand, an index determination is defined as the derivation method through value-added data related to drought through the comparison of the historical data with the current conditions (Heim 2002; Zargar et al. 2011; Eslamian 2014; Hao & Singh 2015). Indices are used in quantifying droughts and their magnitude while at the same time being used as indicators. A comparison of the long-term average with the actual precipitation is regarded as the quickest and easiest way for drought determination. Computation with the percent normal methods is also possible, but it has drawbacks because the calculation is based on the difference of median and means of a dataset and it can produce a difference for shorter periods. For long-term climatic
records, the means and median precipitation is often not the same because the value of precipitation occurrence exceeds by fifty percent which usually occurs in monthly or seasonal precipitation. Percent normal index follows a normal distribution, and seasonal or monthly precipitation scales do not have a normal distribution. Therefore, comparing the differences of the normal or mean may mislead the results. Thus, researchers need to find a better way of computing the moments of distribution related to precipitation by using some historical context. For this objective, drought indices were established to express drought in such a way that they can provide extra information rather than just giving the comparison of the current situation with historical average and water shortage identification related to the duration and intensity of the event. Heim (2012) demonstrated the early 1900s drought indices that become the USA standard drought monitor in 1999. These indices were Munger’s Index, Kincer’s Index Marcovitch’s Index, Blumenstock’s Index, Antecedent Precipitation Index, Moisture Adequacy Index, Palmer’s Index, Crop Moisture Index, Keetch–Byram Drought Index, Surface Water Supply Index, and Drought Monitor, respectively. These indices were developed based on regional and local definitions of droughts. For example, 15 consecutive no rain days, rainfall less than 87% of normal expectancy, and precipitation more than 21 days with less 1/3 normal expectancy. Heim (2012) also used these indices for comparison purposes and monitoring of drought. During the study, he found Blumenstock and Munger’s indices best in measuring drought in the short term, and also it was comprehended that different realizations were produced from different indices. Several drought indices have been developed for drought monitoring which can be found in published literature. For example, meteorological drought indices (Palmer Drought Severity Index (Palmer 1965); Deciles, (Gibbs & Maher 1967), US Drought Monitor, (Svoboda et al. 2002), Standardized Precipitation Index, (McKee et al. 1993); agricultural drought indices (Crop Moisture Index, Palmer (1968); Crop Specific Drought Index, Meyer et al. (1993); Soil Moisture Deficit Index, Narasimhan & Srinivasan (2005)).

The progression of the indices’ development is aimed to find a dimensionless value with meaning to express the severity of the drought. Some of the drought indices are strictly focused on agricultural issues, while others are concerning about the supply and availability of water in a region. Palmer (1965) incorporate regional water balance and developed the Palmer Drought Severity Index (PDSI) for the identification of agricultural and meteorological drought episodes. After that, more indices were developed based on the context of recent drought realization. For example, a multivariate standardized drought index was introduced by (Hao & AghaKouchak 2013) which was based on the copulas concepts. The index combines standardized soil moisture index and SPI to characterize drought probabilistically. A recent study conducted by (Nasab et al. 2018) uses a machine-learning algorithm and developed an integrated drought index called Fuzzy Integrated Drought Index and compared it with Evapotranspiration Anomaly Percentage Index, Precipitation Anomaly percentage index, Soil Moisture Anomaly Percentage index and Runoff Anomaly Percentage Index. They found Fuzzy Integrated Drought Index as a relatively convenient index.

Advantages and limitations of some popular indices

In this section, some popular drought indices like Standardized Precipitation Index (SPI), Standardized Evapotranspiration Index (SPEI), Palmer Drought Severity Index (PDSI), Delices, and Surface Water Supply Index (SWSI) that are majorly used for monitoring and forecasting of dry conditions in the different parts of the word are discussed. Due to their prevalence, they need discussion before the debate of integration or composite side of indices.

SPI

SPI, developed by (McKee et al. 1993), received global attention before the world meteorological organization, 2009 recommendations because many countries around the globe needed to calculate and tracking drought conditions. SPI makes use of historical records of precipitation to establish a probability for the different time lengths. SPI intensity scale has positive and negative values that are linked with surplus and deficit events. When the SPI value is below (−1.0) for a certain period, it is characterized as an initiating drought event. The drought event will persist until the SPI turns positive. SPI is flexible and makes it easier for the computation of both short and long terms periods through the definition of various intervals of time. SPI also makes it appealing because the index can be computed even where data is missing. Distribution can also be developed and used because of the way SPI is computed. In case of missing data, the result is null, and the computer will move to the SPI value that is next if the available data is enough. SPI is primarily calculated for between 1 month and 72 months, but its use is usually for 24 months or less. The flexibility of SPI allows perfect monitoring of agricultural, hydrological, and
meteorological droughts that has various impacts on different time scales. Impacts of time on precipitation deficit gradually affect the water resources. SPI multitude durations are helpful in showing different water feature changes (Zargar et al. 2011). SPI is frequently used in different studies globally (Lloyd-Hughes & Saunders 2002; Ahmad et al. 2004; Pai et al. 2011; Raziei et al. 2013; Vu-Thanh et al. 2014; Wang et al. 2015a, 2015b; Faiz et al. 2018a; Khan et al. 2018). Besides, the World Meteorological Organization workshop, 2009, Beijing, China under the theme to develop the standards for drought early warning, and the recommendations of different experts were to develop the standards and identify the methods for agricultural drought indices. In this scenario, Lincoln’s workshop on multiple sessions was held under the objectives of limitations, drawbacks, and advantages of already developed indices. The main finding of the workshop was that SPI could be used for early drought warnings and also request to the World Meteorological Organization for implementation of this recommendation (Hayes et al. 2011).

**Limitations.** SPI only uses one climate variable (precipitation) which makes it less connected with the ground conditions. Some studies mentioned that potential evapotranspiration should be included because it is a good indicator to assess the ground condition related to the regional climate (Vicente-Serrano et al. 2010). Secondly, long term and accurate precipitation data, as well as pieces of information about local climatological conditions, are necessary for accurate identification of regions that have greater drought tendency.

**SPEI**

SPEI is based on SPI. The only difference is in this index, the author adds a component of temperature for capturing a climate water balance (Vicente-Serrano et al. 2010; Faiz et al. 2020). Thornthwaite (1948) potential evapotranspiration is used to calculate climatic water balance. It has been established that various meteorological parameters can be used in obtaining good PET (potential evapotranspiration) estimates, but in a drought index context, a general water balance estimation is adequate. Estimation of water balance helps in keeping parsimonious calculations and also gives extra data requirements that are useful in actual evapotranspiration determination. Previous studies documented that SPEI can be efficiently used for agricultural drought tracking. SPEI drought studies have been conducted by (Nguyen et al. 2015; Tajbakhsh et al. 2015; Alam et al. 2017; Ertugrul et al. 2017; Khan et al. 2017; Zhao et al. 2017; Faiz et al. 2018c; Mitra et al. 2018; Manzano et al. 2019).

**Limitations:** A simple climatic water balance may overestimate or underestimate the drought conditions. Secondly, some researchers mentioned that SPEI acts similar to SPI when potential evapotranspiration becomes zero (Song et al. 2015; Faiz et al. 2018c). For example, in colder regions where winter temperature mostly below zero the application of SPEI is not suitable.

**PDSI**

PDSI was developed by Wayne Palmer in the 1960s (Palmer 1965) to primarily assess the agricultural drought. PDSI used moisture availability of a region and monitored drought by the use of a water balance equation. PDSI, unlike SPI, has a component of temperature and soil moisture. The temperature data is used for the estimation of PET through the utilization of the thornthwaite approach and default information on soil moisture is derived from soil information (Palmer 1965). Whereas, incorporation of soil information is rendered more challenging as a result of the other variables used to define PDSI. Both SPI and PDSI have a categorization of wet and dry conditions with most values ranging between +4 and −4. The use of both scales allows the users to be familiar with the response of PDSI to the events of precipitation, giving a better realization of the reaction of the index for different regions. PDSI applications have been widely used in literature (Zhai et al. 2010; Vicente Serrano et al. 2011; Ram 2012; Darand 2015; Jamro et al. 2019; Dehghan et al. 2020; Faiz et al. 2020).

**Limitations:** PDSI has a time scale, which is approximately nine months that causes a lag in drought conditions due to the simplified component of soil moisture calculations. A lag application can be used for several months, leading to a drawback in the identification of drought situation that is rapidly emerging. PDSI also has seasonal applications because it does not account for satisfactory precipitation and frozen soils. Therefore, precipitation events are assumed as liquid precipitation. The main limitation of PDSI is that it was primarily developed to use in the Midwest of the USA for initiating in the identification of agricultural droughts. Documentation regarding PDSI limitations can be found in the following studies (Willeke & Hosking 1994; McKee 1995; Guttman 1998). Secondly, due to its wide acceptance, PDSI results are still considered as an approximation due to the simple form of calculation of potential evapotranspiration.
Deciles
To identify and classify droughts, deciles of precipitation are used. In deciles, the historical records are fragmented into multiple portions that represent ten percent of data. When precipitation will fall in the 10% driest record it would refer to 1st decile while the median would be the 5th decile. The straightforward approaches help researchers in defining the dryness conditions of a region and support them to understand the interaction point of the current precipitation regime. A decile approach can be used in monitoring any drought type due to its flexibility of threshold that is established based on the region’s climate.

Limitation. The drawback of using percent normal calculations is that the precipitation can get classified against historical data.

SWSI
As earlier mentioned, one of the major drawbacks of PDSI is miss-considering the calculations of the frozen precipitation. The drawback was addressed by (Shafer & Dezman 1982) in SWSI in the 1980s. SWSI aimed to use for hydrological drought monitoring and addressing the disadvantages of PDSI due to not taking into account frozen precipitation. The disadvantages were addressed through the consideration of the mountainous region’s snowpack together with the melting snows subsequent runoff that ends to the river streams. For calculation of SWSI four inputs are required such as streamflow, precipitation, snowpack, and reservoir storage. Weighted values were given based on total water balance contributions in the Basin, while the scaling is ranged from +4.2 to −4.2 which is very similar to the PDSI. Some authors applied SWSI in their studies for hydrological drought conditions (Kwon & Kim 2010; Steinemann et al. 2015).

Limitations. Although SWSI has many advantages over PDSI, it has drawbacks that limit its widespread use. One of the issues limiting its application is that many inputs are required for SWSI calculation. Therefore, there is an addition or omission of data points over the basin for the assignment of weight to be readjusted. There exists a challenge in comparing different case studies because the calculations are unique for every area of study. SWSI is also not applicable or limited application in the basins due to management practices and water retention in the basins.

APPLICATION OF DROUGHT INDICES
As reviewed above drought indices are extensively used for drought monitoring, dry spells analysis, and performance evaluation around the globe. For example, Wang et al. (2015a, 2015b) used meteorological drought indices (MDIs) like PDSI, SPI, SPEI, DI, Z- index, scPDSI as an indicator in northeastern, China to assess the soil moisture conditions. Similarly, Liu et al. (2018) (North China Plain), Faiz et al. (2018a) (Songhua River Basin), Liu et al. (2016) (Mongolian Plateau), Li et al. (2012) (South China) used MDIs for drought monitoring and their characteristics. Hänsel et al. (2019) used the water balance anomaly index, and a combination of different precipitation indices over Central Europe to analyze the seasonal drought trends and variations. Besides, different studies are also carried out to assess the drought characteristics and dry spells over the Czech Republic, Poland, and Germany (Potop et al. 2014; Osuch et al. 2016; Lüttinger & Feike 2018). Yalti & Aksu (2019) and Eris et al. (2020) use MDIs for drought analysis in Turkey. Their application MDIs suggested that selected indices are best to explain spatio-temporal variability of a river basin or a site. In the south-central United States, Tian et al. (2018) used six MDIs for agricultural drought monitoring and identify that multiple drought indices are necessary for agricultural drought monitoring. Although these studies confirm the applicability of single variable or multiple variable drought indices many researchers point out the drawbacks and reformulate some MDIs with more data input for better assessment of drought characteristics. For instance, Kim et al. (2009) modified the effective drought index to calculate drought characteristics. For that purpose, the author used individual drought event drought duration and severity, runoff, accumulated negative effective drought index. Likewise, Li et al. (2017) reformulate SPEI with pan evaporation data and single variable SPEI is the best option for measuring dry spells when a large amount of data to calculate evapotranspiration is not available for SPEI.

STRENGTHS AND WEAKNESSES OF REVIEWED INDICES
To validate a new drought index, a comparison of traditional drought indices with the new indices is necessary to assess its performance (Azmi et al. 2016). One of the main issues in several countries for monitoring drought is missing data because long term, reliable and consistent records of precipitation cannot be availed. In cases where
the data breaks are existing, SPI can get favorable information. When using SPI, it is possible with time intervals that can make sense of the severity and type of drought likely with the area of study. SPI is an index based on precipitation, and it tends to be applied more often in the identification of hydrological and meteorological droughts episodes with no component of water balance. SPI is useful in the identification and development of drought situations for agricultural drought. Therefore, at a short time scale, SPI responds quickly to find drying conditions. Hence, SPI has flexibility for computation at any period. SPEI helps in updating weekly by use of a moving time window. SPEI also uses the difference between potential evapotranspiration and precipitation in determining a wet or dry period. The flexible nature of SPEI enables it to have a capacity for utilization in monitoring the different drought types as a result of incorporating water balance.

In changing climate, the drought indices change the ways of addressing and monitoring dryness conditions, therefore a comprehensive debate and discussions are necessary for the literature. The indices consider paleoclimatic data apart from written records of climate in understanding the past characteristics of drought. Drought is a constant phenomenon that has different episodes that are regularly occurring in history. Changing climate context is an indication of the continued occurrence of droughts because droughts are natural cycles of climate around the globe. Although drought has been known to be caused by different triggers, some scientists link more severe droughts to changes in climate. The emission of greenhouse gases into the atmosphere causes an increase in air temperature leading to the evaporation of moisture from the land and water resources ceases. Temperatures that make the environment warmer also leads to an increase in evaporation in plant soils affecting the life of plants leading to a reduction in rainfall events. Drought-stricken areas may not experience rainfall, therefore, leading to low absorption of water, which can increase flash floods likelihood. Increased temperatures and uncertain amounts of precipitation distribution can increase the frequency, duration, and intensity of droughts at several locations (Easterling et al. 2000; IPCC 2014).

According to many studies, there is no specific drought index that has the capability of performing appropriately under all circumstances. The studies have also concluded that most drought indices cannot comprehensively evaluate the stress conditions of water for a specific ecosystem. Due to these limitations, it has been recommended in many studies that approach such as aggregation or combination should be used for the derivation of new drought indices that would enhance the accuracy and reliability of these drought indices (Eklund & Seaquist 2015; Hao & Singh 2015; Faiz et al. 2018c; Flint et al. 2018; Shen et al. 2019). The most common aggregation or combination is based on the uses of the blending of objective and subjective drought indices. Secondly, other aggregations and combination approaches may be used for multivariate drought indices. Specific drought indices give different information if not conflicting under different conditions of climate, application perspective, and use of land. In conclusion, there exists no drought index fitting all the various circumstances. Keeping in mind this scenario regarding the application of drought indexes, we also assess the pattern and focus of authors when they used to develop and apply drought index based on combining or aggregation of drought indexes. For this purpose, we take the data from the web of science and analyze the author’s keyword and try to understand their research pattern. Firstly, a simple drought index keyword was searched in the web of science from 1986 to 2019. Two common keywords were found in the database that was ‘monitoring’ and ‘climate change’ and their main focus was on crop yield and dryness conditions (Figure 2(a) and 2(b)).

Likewise, aggregation-based drought indices, have keywords like subjectivity analysis, limited mathematical, and statistical for objectives that were linking with the developed indices’ drawbacks. Therefore, we further reviewed the composite and aggregated drought indices for assessing the researcher’s focus.

**COMPOSITE OR AGGREGATED DROUGHT INDICES**

Given the author’s perspective and web of science database, we have reviewed composite and aggregated drought indices that are developed and applied in different regions of the world and tried to find what were the reasons behind the aggregation of those drought indices. For this purpose, the web of science database was searched for composite, aggregation, combined, modification, and reformulation keywords and then review and main points of the developed composite or aggregated drought indices are highlighted. The basic concept behind integration or composite index is presented in Figure 3.

**Composite index (CI)**

CI was firstly developed by the National Climate Center of China for meteorological drought monitoring by the combination of SPI at one and three-month scales and evapotranspiration (Shu-Yan et al. 2009; Qian et al. 2011).
The application of CI is limited in northeast China because CI takes previous winter accumulated precipitation while spring drought in the region is related to spring precipitation as well as previous winter soil water storage. Therefore, CI failed to represent the occurrence of spring droughts (Song et al. 2014). Thus, CI was reformulated for the spring season by considering previous autumn precipitation. Authors compared spring CI with original CI, scPDSI, and SPI and concluded that spring CI was quite better than these indices while also documenting several uncertainties that are related to soil moisture data, and spring disaster records, etc (Song et al. 2014). In spring CI, the author concluded that SPI which was based on the previous year (Sep-Nov) precipitation and April or May precipitation instead of taking one and three-month SPI is better to detect droughts in colder environments.

Figure 2 | (a) Application of drought indexes based on authors keyword selection obtained from the web of science core collection record from 1986–2019. WOS document information was imported into VOSviewer to generate bibliometric networks. (b) Author’s focus based on keyword selection obtained from the web of science core collection record from 1986–2019.
Composite drought index (CDI)

Waseem et al. (2015) established CDI based on the possible driest and wettest conditions and individual variable entropy to reflect the agricultural, meteorological, and hydrological anomalies. The developmental concept of CDI is to provide an effective methodology that can present drought dynamics without considering transformation, assumptions, feature extraction techniques, and cumbersome empirical derivations. The variables such as precipitation, streamflow, land surface temperature, and normalized difference vegetation index were used to assess the drought conditions in South Korea (Waseem et al. 2015). CDI is well compared with ADI (Bazrafshan et al. 2014). The authors documented that CDI is temporally flexible and physically sound and associated with climatic conditions and possible variants of the study area. But the CDI application in any other region is not found which can warrant the mentioned pros of CDI.

Aggregate drought index (ADI)

ADI was developed based on PDSI limitations such as empirical formulation and geographical location of a specific area (US Midwestern states), and snowfall process, and SWSI shortfalls in considering soil moisture and evaporation. ADI uses 5 to 6 variables such as snow water content, evapotranspiration, reservoir storage, soil moisture, streamflow, and precipitation (Keyantash & Dracup 2004). ADI’s direct mathematical approach can assess the agricultural water shortage, hydrological and meteorological droughts in aggregated perspectives. A comparison of ADI with PDSI revealed a satisfactory correlation (between 0.78 and 0.65). (Wang et al. 2018) developed ADI using evapotranspiration, potential evapotranspiration, SPI, normalized difference precipitation index, soil moisture, and SPEI based on the argument that drought had larger spatial heterogeneity. Although the author got the best results of different growth stages of winter wheat but did not compare with earlier developed ADI and other indices. Secondly, larger data is required for the application of ADI (developed by Wang et al. 2018) which may limit its applicability.
Integrated drought condition index (IDCI)

Shen et al. (2019) used vegetation conditions, soil moisture, and SPEI on a 3-month scale to integrate drought index. Authors argue that there is a knowledge gap for agricultural drought hazards but the study did not evaluate and analyze the risk assessment of hazards. IDCI was compared with scaled crop yields index, soil moisture conditioned index, and vegetation condition index. IDCI performs better than these indices and IDCI can be used for agricultural drought monitoring.

Multivariable composite drought index (MCDIs)

A remote sensing approach is used to develop MCDIs (Liu et al. 2020). Normalized difference vegetation index, soil moisture, and satellite precipitation are integrated for MCDIs. MCDIs show good agreement with moisture index, SPI, and SPEI at different time scales. The index is effective for assessing meteorological and agricultural drought in semi-tropical monsoon climate regions. The concept behind MCDIs is that indices are region-dependent and cannot reflect and capture the role of a single variable in drought formation.

Microwave integrated drought index (MIDI)

Zhang et al. (2017a) developed MIDI using remote sensing data to overcome the spatial coverage limits in an area that has high spatial variability of in situ stations. MIDI was integrated with land surface temperature, soil moisture, and precipitation for short-term droughts in a semi-arid region of China. MIDI and SPI reflect similar temporal changes and spatial patterns at a one and three-month scale. MIDI is best for cropland and grassland areas to measure short-term meteorological droughts.

Process-based accumulated drought index (PADI)

PADI was integrated with vegetation conditions, soil moisture, precipitation, and crop growth stages (Zhang et al. 2017b). The authors provide solid arguments about univariate and bivariate analyses used in the drought system. Both analyses have shortcomings therefore the multivariate idea is used to develop PADI. PADI was compared with PDSI and SPI and found a satisfactory correlation among them. PADI also correlated with wheat yield loss and found a good correlation.

Nonlinear aggregated drought index (NADI)

NADI is developed based on limitations that linear principal component analysis represents less variance in the data (Barua et al. 2012). Several hydro-meteorological variables (streamflow, rainfall, storage reservoir volume, potential evapotranspiration, soil moisture content) are tested as input in NADI. The primary purpose of NADI was to enhance ADI methodology (Keyantash & Dracup 2004) and forecasting capabilities.

Multivariate integrated drought index (MIDI)

Chang et al. (2016) constructed MIDI to investigate drought risk by the integration of SPI, modified Palmer drought severity index, runoff anomaly percentage, and precipitation anomaly percentage. The basis of MIDI is that drought conditions may reflect different situations on a 6-month scale compared to a 1-month scale because the cumulative effect of water shortage has also impact droughts in different periods.

CONCLUSIONS

Identification and monitoring of droughts using diverse indexes are very important for the proper management of impending droughts. Until now there has been no widely agreed drought index among researchers. Therefore, researchers are trying to modify and reconstruct a complete, simple, and robust drought index for effective use and planning of the management of water resources. However, in the terrestrial ecosystem, it is much more complex to assess water stress and monitoring dry conditions using a single variable or sole drought indicator. Hence, the researchers used different drought indexes and construct an integrated or composite drought index for evaluation and monitoring of drought.

The reviewed composite or aggregated indices revealed that the authors are mainly focused on regional climatic, environmental conditions, data use, and differences of theoretical backgrounds in the development of indices. Researchers are mostly engrossed in drought impact on agriculture and crop yield and soil moisture. They did not compare developed indices with other composite or integrated indices. Mostly the indices were compared with an early developed single or multiple variable drought index (SPEI, SPI, PDSI). While the developer authors did not mention the limitations such as data, which is a big problem while applying these indices in
other regions. Therefore, there is still comprehensive work needed for the simple integration of drought indexes for general applications.

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CONFLICT OF INTEREST

The authors declare no potential conflict of interest.

DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

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