A review of drought indices

Amin Zargar, Rehan Sadiq, Bahman Naser, and Faisal I. Khan

Abstract: Drought is a stochastic natural hazard that is instigated by intense and persistent shortage of precipitation. Following an initial meteorological phenomenon, subsequent impacts are realized on agriculture and hydrology. Among the natural hazards, droughts possess certain unique features; in addition to delayed effects, droughts vary by multiple dynamic dimensions including severity and duration, which in addition to causing a pervasive and subjective network of impacts makes them difficult to characterize. In order manage drought, drought characterization is essential enabling both retrospective analyses (e.g., severity versus impacts analysis) and prospective planning (e.g., risk assessment). The adaptation of a simplified method by drought indices has facilitated drought characterization for various users and entities. More than 100 drought indices have so far been proposed, some of which are operationally used to characterize drought using gridded maps at regional and national levels. These indices correspond to different types of drought, including meteorological, agricultural, and hydrological drought. By quantifying severity levels and declaring drought's start and end, drought indices currently aid in a variety of operations including drought early warning and monitoring and contingency planning. Given their variety and ongoing development, it is crucial to provide a comprehensive overview of available drought indices that highlights their difference and examines the trend in their development. This paper reviews 74 operational and proposed drought indices and describes research directions.

Key words: drought, drought characterization, drought indices, meteorological drought, vegetation indices.

Résumé : La sécheresse est un hasard stochastique naturel déclenché par un manque intense et persistant de précipitation. À la suite d'un phénomène météorologique initial, on observe des impacts subséquents sur l'agriculture et la météorologie. Parmi les hasards naturels, les sécheresses affichent certaines caractéristiques uniques; en plus des effets à retardement, les sécheresses varient selon de multiples dimensions dynamiques incluant la sévérité et la durée, lesquelles en plus de causer un ensemble d'impacts envahissants et subjectifs les rendent difficiles à caractériser. Pour son aménagement, la caractérisation de la sécheresse s'avère essentielle en considérant les analyses rétrospectives (p. ex. sévérité vs analyse des impacts) aussi bien que la planification prospective (p. ex. évaluation des risques). L'adaptation d'une méthode simplifiée par indices de sécheresse a facilité la caractérisation de la sécheresse pour divers utilisateurs et institutions. On a proposé jusqu'ici pas moins de 100 indices de sécheresse, dont certain utilisés de façon opérationnelle pour caractériser la sécheresse en utilisant des cartes quadrillées aux échelles régionales et nationales. Ces indices correspondent à différents types de sécheresse, incluant la sécheresse hydrologique et la sécheresse météorologique agricole. En quantifiant les degrés de sévérité et en communiquant le début et la fin, les indices de sécheresse aident actuellement à la conduite de diverses opérations incluant l'avertissement hâtif de la sécheresse et son suivi, ainsi que la planification des contingences. Compte tenu de leur variété et de leur développement continu, il est essentiel de présenter une revue complète des indices de sécheresse disponibles mettant en lumière leurs différences et d'examiner la tendance de leur développement. Cette publication passe en revue 74 indices de sécheresse opérationnels ou proposés et décrit les directions de recherche.

Mots-clés : sécheresse, caractérisation de la sécheresse, indices de sécheresse, sécheresse météorologique, indices de végétation.

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1. Introduction

Drought is a stochastic natural phenomenon that arises from considerable deficiency in precipitation. Among natural hazards, drought is known to cause extensive damage and affects a significant number of people (Wilhite 1993). To reduce the damage from drought, it is crucial to characterize droughts. Drought characterization enables operations such as drought early warning (Kogan 2000) and drought risk analysis (Hayes et al. 2004), which allow improved preparation and contingency planning.

Drought *indices* are quantitative measures that characterize drought levels by assimilating data from one or several variables (*indicators*) such as precipitation and evapotranspiration into a single numerical value. Such an index is more readily useable than raw indicator data. The nature of drought indices reflects different events and conditions; they can reflect the climate dryness anomalies (mainly based on precipitation) or correspond to delayed agricultural and hydrological impacts such as soil moisture loss or lowered reservoir levels. In addition, the categorization of drought indices can also be based on the data and technology used. For example, a con-

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siderable number of indices use remote-sensing imagery to detect vegetation health as indicator of drought.

Using this relatively simple methodology, drought indices have developed into the primary tool for communicating drought levels among involved entities. Some prominent indices are currently operationally used for the publication of weekly grid-based drought condition maps, which are publicly accessible.

Since the development of a drought index can conceptually be based on multiple factors (e.g., drought's nature and characteristics and the impacts considered); multiple drought indices have been developed (more than 150, Niemeyer 2008). This is in addition to continuing technological development (especially in field of remote-sensing), the need to customize indices to specific climatic and hydrologic regimes (e.g., Vicente-Serrano et al. 2010), and the recent trend in aggregating existing indices with new ones to cover more impacts and applications (e.g., Brown et al. 2008).

To provide researchers with a comprehensive listing and description of drought indices, this work reviews 74 indices out of the nearly 150 available. Using nine primary references (Hayes 2006; Hayes et al. 2000; Heim 2002; Kallis 2008; Keyantash and Dracup 2002; Niemeyer 2008; Quiring 2009; Steinemann 2003; Steinemann et al. 2005; Tsakiris et al. 2007), a preliminary list of drought indices was compiled from which prominent drought indices were selected and thereafter described. This list includes various operational, research, and proposed drought indices. The trend within the development of each index category is further described.

2. Drought characterization concepts

The variety of proposed drought indices reflects the variability in perceptions about drought. This includes the basic definition of drought, which varies among different applications. For example, agricultural drought primarily focuses on absent soil moisture content, while hydrological drought examines the lagged effects of precipitation deficiency on various water features. This section provides the fundamental concepts based on which drought indices have been developed.

2.1 Definition and types

2.1.1 Drought definition

The definition of drought is itself complex; although the majority of people may consider extreme precipitation shortage as drought, how to objectively characterize it for planning and management is a challenging issue. Drought can generally be defined as the extreme persistence of precipitation deficit (González and Valdés 2006) over a specific region for a specific period of time (Beran and Rodier 1985; Correia et al. 1994). In addition to the elements of 'persistence' of 'substantial precipitation deficit', 'bounded by time and space', definitions have expanded to include impacts on environment and society (Tsakiris and Vangelis 2004). In this viewpoint, drought impacts are functions of both the enormity of the water shortage as well as susceptibility on ground conditions. Wilhite (2004) emphasizes the human demand placed on water supply. Being affected by drought is thus a context-dependent matter. Part of the complexity in drought definition stems from such subjectivity of extent of drought impacts (Eierdanz et al. 2008). This challenge is reflected in the conceptual development of nonmeteorological drought indices; although more than 91 drought impacts can be identified (NDMC 2006*a*), drought indices make use of a handful of impact indicators including vegetation health, evapotranspiration or water resources levels.

It is also important to differentiate between *conceptual* and *operational* definitions of drought (Wilhite and Glantz 1985). Conceptual definitions are formulated in general terms for overall understanding and establishing drought policy (NDMC 2006*b*). Operational definitions of drought (e.g., agricultural or hydrological) objectively define criteria for drought start and end and severity for a specific application.

2.1.2 Drought types and characteristics

By implementing an operational definition of drought, three main physical drought types were established: meteorological, agricultural, and hydrological droughts. In a broad definition, these droughts occur in a particular order (Fig. 1); precipitation deficiency instigates meteorological drought, which subsequently impacts soil moisture content (i.e., agricultural drought). Low recharge from the soil to water features such as streams and lakes causes a delayed hydrological drought. Figure 1 provides a general schematic of this sequence.

In addition to type, droughts are fundamentally characterized in three dimensions: severity, duration, and spatial distribution (see the following). Additional characteristics include: frequency, magnitude (cumulated deficit), predictability, rate of onset, and timing. Unfortunately, usage of the terms severity, intensity, and magnitude is not universal, and sometimes their meanings are switched. For example, Yevjevich (1967) uses the vocabulary of run-sum, run-length, and run-intensity for the associated terms of severity, duration, and magnitude used by Dracup et al. (1980). Here, we use the widely adopted terminology of Salas (1993):

Duration: Depending on the region, drought's duration can vary between a week up to a few years. Because of drought's dynamic nature, a region can experience wet and dry spells simultaneously when considering various timescales. As such, in shorter durations the region experiences dryness or wetness, while in longer-term, it experiences the opposite (NCDC 2010).

Magnitude: The accumulated deficit of water (e.g., precipitation, soil moisture, or runoff) below some threshold during a drought period.

Intensity: The ratio of drought magnitude to its duration.

Severity: Two usages are provided for drought severity:

> the degree of the precipitation deficit (i.e., magnitude), or the degree of impacts resultant from the deficit (Wilhite 2004).

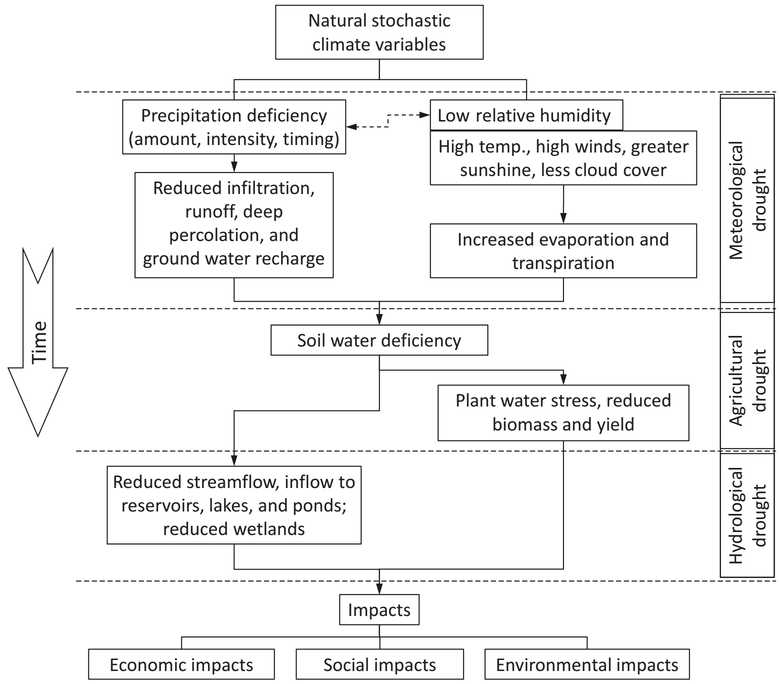
Geographic extent: The areal coverage of the drought which is variable during the event. This area can cover one or several pixels (cells), watersheds or regions.

Frequency (return period): The frequency or return period of a drought is defined as the average time between drought events that have a severity that is equal to or greater than a threshold.

2.2 Drought indicators

Along with precipitation deficit, additional variables such as evapotranspiration and stream flow are also used to more

Fig. 1. The general sequence for the occurrence of different drought types. Modified from NDMC (2006*b*).



comprehensively characterize drought. Using different models (e.g., water balance/hydrological models), such variables or *indicators* are used in combination to derive a drought index. Such indicators can be meteorological, hydrological, or water supply-and-demand in nature. Meteorological indicators include precipitation and cloud cover; hydrological indicators include stream flow and groundwater level; water supply-and-demand indicators include reservoir storage. In practice, however, some indicators such as precipitation, potential evapotranspiration, and soil- and vegetation-cover characteristics have had wider applications and influence (Tsakiris and Vangelis 2005).

3. Drought characterization using drought indices

Several methodologies for drought characterization exist; however, using drought indices is prevalent (Tsakiris et al. 2007). Drought indices are calculated from assimilating drought indicators into a single numerical value. A drought index provides a comprehensive picture for drought analysis and decision-making that is more readily useable compared with raw data from indicators (Hayes 2006). More than 150 drought indices have been developed (Niemeyer 2008) and additional indices have recently been proposed (Cai et al. 2011; Karamouz et al. 2009; Rhee et al. 2010; Vasiliades et al. 2011; Vicente-Serrano et al. 2010).

Operationally, using an index for drought characterization serves the following purposes:

- drought detection and real-time monitoring (Niemeyer 2008)
- declaring the beginning or end of a drought period (Tsakiris et al. 2007)
- allowing drought managers to declare drought levels and instigate drought responses measures;
- drought evaluation (Niemeyer 2008)
- representing the concept of drought in a region (Tsakiris et al. 2007)
- correlating with quantitative drought impacts over variable scales of geography and time; and
- facilitating the communication of drought conditions among various interested entities.

3.1 Taxonomy of drought indices

Commonly, drought indices are categorized based on the type of impacts they relate to. The taxonomy can also be based on the variables they relate to (Steinemann et al. 2005) or use of disciplinary data (Niemeyer 2008). Three popular categories are meteorological, agricultural and hydrological drought indices. Niemeyer (2008) adds three categories to this list: comprehensive, combined and remote-sensing-based drought indices. Comprehensive drought indices use a variety of meteorological, agricultural and hydrological variables to draw a comprehensive picture of drought. The Palmer Drought Severity Index (PDSI) is an example of this approach. Remote-sensing-based drought indices use information from remote-sensing sensors to map the condition of the land (e.g., the Normalized Difference Vegetation Index, NDVI, Tucker (1979)). Combined (also termed *hybrid* and *aggregate*) drought indices are derived by incorporating existing drought indicators and indices into a single measure. The US Drought Monitor (Svoboda et al. 2002) is an example.

This paper is based on the categorization by Niemeyer (2008) omitting the “comprehensive” category.

4. Drought indices

4.1 Major operational drought indices

This section describes six drought indices that are frequently used in forecasting, monitoring, and planning operations. Because of their prevalence, they were warranted a longer description.

Table 1. Phenomena reflected by specific-duration standardized precipitation indices (SPI) and their applications (NDMC 2006*c*)

SPI duration	Phenomena reflected	Application
1 month SPI	Short-term conditions	Short-term soil moisture and crop stress (especially during the growing season)
3 month SPI	Short- and medium-term moisture conditions	A seasonal estimation of precipitation
6 month SPI	Medium-term trends in precipitation	Potential for effectively showing the precipitation over distinct seasons. e.g., for California, the 6 month SPI can effectively indicate of the amount of precipitation from Oct. to Mar.
9 month SPI	Precipitation patterns over a medium time scale	If $SPI_9 < -1.5$ then it is a good indication that substantial impacts can occur in agriculture (and possibly other sectors)
12 month SPI	Long-term precipitation patterns	Possibly tied to streamflows, reservoir levels, and also groundwater levels

Some drought indices specifically reflect one type of impact or application, while others can be configured to correspond to varying impacts and thus drought type. For example, SPI, which is a meteorological drought, can be deployed for longer time scales to reflect agricultural and hydrological droughts/impacts.

Percent of normal: The percent of normal precipitation is a meteorological drought index that describes the drought as the precipitation deviation from the normal (average). The normal usually corresponds to the mean of the past 30 years. Percent of normal is calculated by dividing a given precipitation by the normal. The time scale of the analysis can vary from a single month to a year. The main advantage of this index is its simplicity and transparency, which makes it favourable for communicating drought levels to the public (Keyantash and Dracup 2002). The percent of normal enables analysis for a single region and a specific period within a year. The statistical construct of this index has been criticized for inconsistency in two aspects (Hayes 2006). First, since no statistical transformation is used for the distribution of the precipitation record, the difference between the median and the mean value can undermine its accuracy. Second, since the distributions for seasons and regions are different, this index cannot be used to compare drought across seasons and regions. As such this method lacks robustness required for operational use in planning and management.

Deciles: The method of deciles or 10%iles is based on dividing the distribution of monthly record precipitation into 10% parts (Gibbs and Maher 1967). Extended lengths of precipitation data record are required for accurate estimation. Deciles may be computed for any chosen period or window. Different categories of drought exist in the Australian Drought Watch Service. Generally, deciles method considers only the lowest 10% and two categories are used for characterizing rainfall deficiency: *severe* and *serious*. The former indicates the lowest 5% of recorded rainfall and the latter, the second lowest 5%.

Standardized Precipitation Index (SPI): SPI (McKee et al. 1993) is a popular meteorological drought index that is also solely based on precipitation data. Similar to the percent of normal, SPI compares precipitation with its multiyear average. SPI overcomes the discrepancies resulting from using a nonstandardized distribution by transforming the distribution of the precipitation record to a normal distribution. For this, the precipitation record is first fitted to a gamma distribution that is then transformed into a normal distribution using an equal-probability transformation. The mean is then set to zero and as such, values above zero indicate wet periods and values below zero indicate dry periods. For any given drought, its score in SPI represents how many standard deviations its cumulative precipitation deficit deviates from the normalized average (Drought Watch 2010). If a value of less than zero is consistently observed and it reaches a value of –1 or less, a drought is said to have occurred (McKee et al. 1993). An important aspect is the development of the SPI is its ability to calculate drought levels for different time scales. McKee's index can be computed for any time period, however typically it is applied for the 3, 6, 12, 24, and 48 month periods. Because over time precipitation deficit gradually and variably affects different water resources (e.g., stream flow, groundwater, and snowpack), the multitude of SPI durations can be used to reflect change in different water features. Table 1 shows different time scales of SPI with related effects (NDMC 2006*c*).

In December 2009, the Inter-Regional Workshop on Indices and Early Warning Systems for Drought was held (*Lincoln Declaration on Drought Indices*, WMO 2009). One of the goals of the workshop, represented by 22 countries, was to help determine the best "meteorological" index and then recommend that all national meteorological services use this index. This would make comparisons in drought severity among countries in the same region, and also among regions possible. The SPI was chosen by participants as the one to use (Hayes et al. 2011).

For SPI, 30 years record is required but 50 years has been recommended (Guttman 1999). Currently, this index has been widely adopted for research and operational modes. The advantages and disadvantages of the six major operational drought indices are summarized in Table 2.

Palmer Drought Severity Index (PDSI): PDSI (Palmer 1965) is a popular meteorological drought index, especially in the US. The PDSI bases its concept of drought on water supply-and-demand instead of precipitation anomaly. Emphasis is on abnormalities in moisture deficiency rather than weather anomalies (Guttman 1999). PDSI uses precipitation, temperature, and the local available water content (AWC) data for soil. Using these inputs, PDSI computes four terms in the water balance equation: evapotranspiration, runoff, soil recharge, and moisture.

US Drought Monitor (USDM): The USDM (Svoboda et al. 2002) is a composite drought index. The USDM integrates multiple indices such as SPI and PDSI as well as indicators such as vegetation and hydrologic conditions into a weekly map of drought. This information is later subjected to expert interpretation for refinement. Because of its composite nature, USDM can respond to the needs of various water

Table 2. Advantages and disadvantages of popular drought indices.

DI, source and inputs	Advantages	Disadvantages
SPI (McKee et al. 1993) Precipitation	Simplicity; SPI relies only on precipitation data	Uses only precipitation, loosely connected to ground conditions. Potential evapotranspiration is a valuable additional indicator (Hu and Willson 2000; Tsakiris and Vangelis 2005; Vicente-Serrano et al. 2010)
	As SPI is adaptable for the analysis of drought at variable time scales; it can be used for monitoring agricultural and hydrological	
	Comparing precipitation departure from normal for various regions with highly different climates is possible	Limitations of the precipitation data including accuracy of measurements, the number of gauging stations and length of the record
	Equally represents both wet and dry climates and hence can be used for monitoring wet periods	Lacks the ability to identify regions with greater tendency to droughts; Requires knowledge of the local climatology
PDSI (Palmer 1965) Precipitation, temperature	More comprehensive than precipitation-only indices; evapotranspiration and soil moisture are also considered	Arbitrary selection of beginning and end intensity values and algorithms
		Less transparency because of more sophisticated computation
	Can use basic data for calculation: precipitation and air temperature for which records for a long time back exist	Calibrated for US Great Plains' conditions; limited applicability in locations with climatic extremes, mountainous terrain, or snow-pack unless calibrated
	Most effective where impacts sensitive to soil moisture	Variable performance across regions and time periods
	Factors in antecedent conditions	Applicability to regions with extreme climate (e.g., highly variable rainfall or runoff, mountainous areas)
		Handling of snow and soil freeze
		Neglecting the lag between rainfall and runoff Lag
		PDSI uses the Thornthwaite method to estimate potential evapotranspiration. Although this index has had wide acceptance, it is still considered an approximation (NDMC 2006*b*)
		All Palmer Indices are hardly appropriate for droughts within with water management systemsas they exclude water storage, snowfall, and other supplies. They also do not take human water balance impacts such as irrigation into account (Steinemannet al. 2005)
NDVI (multiple) Visible red band, near infrared bands	Simple algorithms	**Resolution:** The resolution of NDVI datasets extracted from MODIS sensor is 250 m and lacks accuracy for some applications. These include monitoring change in riparian buffer zones and urban areas (Nagler et al. 2005)
	While resolution is high (1 km) (compared to weather stations) AVHRR covers a large land area (L Ji and Peters 2003)	**Soil conditions effects:** NDVI is sensitive to darker and wet soil background (Huete et al. 1985). In wet conditions, the reflectance may not be equal in two bands and as such, the NDVI may vary with soil moisture variations.
	Current NDVI algorithms can reduce noise from atmospheric conditions (e.g., clouds) and effects of the sun-surface geometry with respect to the sensor. It hence broadly distinguishes vegetated areas from other surfaces.	**Nonlinearity:** Similar to other ratio-based standardized vegetation indices (SVI), NDVI suffers from scaling and nonlinearity **Saturation:** In dense vegetation and (or) multilayered canopy, where large biomass is present NDVI tends to saturate.
	NDVI actually measures dryness (rather than interpolation or extrapolation).	**Atmospheric interference (atmospheric path radiance):** Atmospheric interference can contaminate pixels. This contamination can be due to cloud, seasonal smoke, aerosols, haze, etc. Currently available algorithms are capable of partially removing the contaminated pixels.
		Anisotropy: Surfaces, especially vegetation variably reflect light in different directions. The effects of variable geometry of illumination and the position of the vegetation relative to the swath of the sensor need to be considered. Burgess et al. (1995)
		Vegetation stress and moisture correlation: Vegetation stress is influenced by more factors than moisture conditions alone. These include regional rainfall patterns and soil type as well events such as floods, insect infestation, wildfire, etc. L Ji and Peters (2003).

users including water planners and the agriculture industry. USDM is currently widely used in the organizational level, for research, and by the media. The index is increasingly considered outside the US.

Normalized Difference Vegetation Index (NDVI): NDVI is a remote sensing-based index that measures vegetation conditions (Rouse et al. 1974). NDVI uses the advanced very high resolution radiometer (AVHRR) reflected red and near-infrared channels to calculate if the vegetation is healthy, or unhealthy and sparse (e.g., suffering from drought or insect infestation). The formula for NDVI is given in (eq. 1):

$$[1] \qquad \mathrm{NDVI} = \frac{\mathrm{NIR} - R}{\mathrm{NIR} + R}$$

where NIR is near-infrared spectral reflectance and R is the visible red spectral reflectance. Under healthy conditions, chlorophyll (the green substance that produces carbohydrates in plants) absorbs light, reflecting less R. Lower R values result in higher NDVI value. Unhealthy plants reflect higher R resulting in lower NDVI. NDVI has extensively been used is a base index for a number of remote sensing indices that similarly measure vegetation conditions, e.g., Vegetation Condition Index, VCI (Kogan 1990) (refer to Tables 4 to 6).

4.1.1 Performance of drought indices

Some studies have compared the performance of the six drought indices. Quiring and Papakryiakou (2003) compared four drought indices: PDSI, Palmer's Z-Index, SPI and NOAA Drought Index (Strommen et al. 1980) to find the Palmer's Z-index (cf. Sect. 4.2) most suitable index to monitor agricultural drought in Canadian prairies. Additional studies that compared prominent drought indices are summarized in Table 3.

In general, according to a survey performed by Steinemann et al. (2005), the selection of an appropriate drought index driven by the following factors: suitability for the drought type under study; data availability, cost, consistency (quality) and practicality, clarity, and scientific validity; temporal and spatial sensitivity (considers both duration- and region-wise variability), and specificity (specific duration and spatial scale, e.g., a watershed versus a climatic division); having well-defined thresholds and criteria (for drought start and end); and statistical consistency (within drought levels and with other indices). Quiring (2009) (Keyantash and Dracup 2002; Narasimhan and Srinivasan 2005) consider six criteria for the evaluation of meteorological drought indices: robustness, tractability, transparency, sophistication, extendability, and dimensionality.

4.2 Other notable drought indices

Other notable drought indices are summarized in Table 4 (introduced prior to year 2000) and Table 5 (introduced after year 2000). Additional drought indices and indicators are comprehensively summarized in Table 6. In the following section, the trend in the development of drought indices is discussed under each drought type category.

5. The development of drought indices

5.1 Meteorological, agricultural, and hydrological drought indices

Meteorological drought indices: The development and implementation of a drought index heavily depends on data availability (Steinemann et al. 2005). Earlier drought indices used meteorological data readily available from synoptic meteorological stations (Niemeyer 2008). These include precipitation-only indices such as RAI (Van-Rooy 1965), BMDI (Bhalme and Mooley 1980), DSI (Bryant et al. 1992), NRI (Gommes and Petrassi 1994), EDI (Byun and Wilhite 1999), and DFI (González and Valdés 2006). For reasons such as

Table 3. Comparison of major drought indices.

Reference(s)	Drought indices and preference	Application and study area	Notes
Guttman (1998)	**SPI** > PDSI	Comparison of drought indices in the USA	Data for 1035 sites within the contiguous USA was used. SPI was recommended due to reasons of simplicity, spatially consistency, its probabilistic nature useful in risk and decision analyses, and being adjustable to user defined time periods of a user's interest. PDSI was found very complex, inconsistent spatially, difficult to interpret, and fixed time periods.
Hayes et al. (1999)	**SPI** > PDSI	1996 drought in southern plains and southwestern USA	SPI is simpler and more versatile; it is flexible for observing different timescales. Useful for different stakeholders for either short- or long-term. SPI demonstrated both the regional and the local development of the drought from late 1995. SPI demonstrated the drought's onset and severity at least 1 month in advance. SPI is not solution for all; it needs to be used in conjunction with PDSI and remote sensing input.
Hayes et al. (2000)	**SPI** > PDSI	Southern plains and southwestern United States, 1996, and California, 1997	SPI provides a clear quantitative assessment of the three main drought dimensions: intensity, duration, and spatial extent. Capable of near real-time monitoring
Keyantash and Dracup (2002)	Among six meteorological indices, **deciles** and **SPI** ranked top; PDSI ranked last.	Evaluation of drought indices for Willamette Valley and North Central climate divisions of Oregon	Meteorological, hydrological and agricultural drought indices were evaluated using six performance criteria: robustness, tractability, transparency, sophistication, extendability, and dimensionality.

Table 4. Additional notable drought indices (P: precipitation, SF: streamflow/runoff, SP: snowpack, ReS: reservoir storage, T: temperature, ET: evapotranspiration, SM: soil moisture, BT: brightness temperature, EV: Evaporation, VWC: Vegetation Water Content, M: Meteorological, H: Hydrological, A: Agricultural, RS: remote sensing, NIR: Near-Infrared and SWIR: Short Wave Infrared).

		Inputs				
Drought index and reference	**Type**	**P**	**T**	**SF**	**other**	**Notes**
Z-index Palmer (1965)	M	•	•	•	SM, ET	Monthly standardized anomaly of available moisture; intermediate term within PDSI (cf. Section 4.1); used as for monitoring short-term droughts
Palmer Modified Drought Index (PMDI) Palmer (1965)	M	•	•	•	SM, ET	Modified PDSI; main difference is in the calculated beginning and ending time of drought/wet periods; compared to PHDI responds more quickly and can be used for real-time monitoring
Keetch-Byram Drought Index (KBDI) Keetch and Byram (1968)	M	•	•			Analyzes P and SM in the water budget model; used by fire control managers to monitor forest fires
Effective Drought Index (EDI) Byun and Wilhite (1999)	M	•				Developed in response to weaknesses in then-available drought indices, weaknesses include imprecision in the drought beginning, ending and accumulated stress; ignoring the aggravating effects of runoff and ET; and incapability for real-time monitoring because of being monthly based. $EP = \sum_{n=1}^{i} \frac{\sum_{m=1}^{n} P_m}{n}$; EP = effective precipitation, i = duration of summation (number of dry days + 365), P_m = precipitation of m days before DEP = EP – MEP; DEP = deviation of EP; MEP = mean of EP $SEP = \frac{DEP}{St(EP)}$; SEP = standardized DEP, St (EP) = standard deviation of daily EP
Palmer Hydrological Drought Index (PHDI) Palmer (1965)	H	•	•	•	SM, ET	Analyzes precipitation and temperature in the PDSI water balance model; compares meteorological and hydrological drought across space and time (Heim 2002)
Surface Water Supply Index (SWSI) Shafer and Dezman (1982)	H	•		•	SP, ReS	Developed in response to PDSI's limitations for mountain snow hydrology; calculates the weighted average of the standardized anomalies for P, ReS, SP, and runoff, the four primary features in the surface water budget; used for river basins in western USA
Reclamation Drought Index (RDI) Weghorst (1996)	H	•	•	•	SP, ReS	Similar to SWSI, however incorporates temperature-variable demand and duration into the index; calculated basin-wise.
Crop Moisture Index (CMI) Palmer (1968)	A	•	•			Analyzes precipitation and temperature in a water balance model
Crop Specific Drought Index (CSDI) Meyer et al. (1993)	A				P, T, ET	Requires soil and crop phenology information in addition to climatological data; estimates soil water availability for different zones and soil layers by daily intervals. CSDI-based indices include: Corn Drought Index (CDI) (Meyer et al. (1993) and Soybean Drought Index (SDI) (Meyer and Hubbard 1995)
Crop Water Stress Index (CWSI) Idso et al. (1981); Jackson et al. (1981)	RS				RS	$CWSI = 1 - \frac{AET}{PET}$ where AET = actual ET and PET = potential ET (Jackson 1981). The terms are replaced by the difference in canopy and air temperature. Applied for irrigation scheduling.
Normalized Difference Infrared Index (NDII) Hardisky et al. (1983)	RS				NIR, SWIR	NDII is highly correlated with canopy and leaf water content (Equivalent Water Thickness, EWT); EWT is related to VWC; NDII is used for monitoring VWC. $NDII = \frac{R_{850} - R_{1650}}{R_{850} + R_{1650}}$; R_{850} = the land–surface reflectance of the NIR channel; R_{1650} = the land–surface reflectance at 1650 nm
Vegetation Condition Index (VCI) Kogan (1990)	RS				NDVI	Determines the departure of current NDVI from the minimum NDVI with respect to long-term NDVI; measures the health of vegetation; (used in USDM); VCI for week/month j is calculated from: $VCI_j = \frac{NDVI_j - NDVI_{min}}{NDVI_{max} - NDVI_{min}} \times 100$; $NDVI_{max}$ and $NDVI_{min}$ = the maximum and minimum NDVIs, respectively, in the record for the specific month/week; $NDVI_j$ is the NDVI for the month under study

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Table 4 (*concluded*).

Drought index and reference	Type	Inputs P	T	SF	other	Notes
Temperature Condition Index (TCI) Kogan (1995)	RS				BT	VCI was modified to use the brightness temperature instead of NDVI as input; determines the deviation the month from recorded maximum; the idea is the higher the temperature, the higher the drought $TCI_j = \frac{BT_{max} - BT_j}{BT_{max} - BT_{min}} \times 100$; BT_{max} and BT_{min} = the maximum and minimum BTs, respectively, in the record for the specific month/week; BT_j = month *j*'s BT
Vegetation Health Index (VHI) Kogan (1995)	RS				VCI, TCI	Combines VCI and TCI; uses a weight factor *a* for the contributions of VCI and TCI's; *a* is set to 0.5 lacking information; found more effective than other vegetative drought indices (Kogan 1990; 2001) $VHI = aVCI + (1 - a)TCI$
Normalized Difference Water Index (NDWI) Gao (1996)	RS				NIR, SWIR	Complementary to NDVI; determines VWC based on physical principles. $NDWI = \frac{NIR - SWIR}{NIR + SWIR}$; NIR = reflectance (radiance) for NIR; SWIR = reflectance (radiance) for SWIR

better correlation with drought impacts and accounting for temporal trends in temperature, additional meteorological variables have been considered. These include modifications to SPI (McKee et al. 1993), to develop the more comprehensive RDI (Tsakiris and Vangelis 2005) that incorporates evapotranspiration resulting in better association with impacts from agricultural and hydrological droughts. Vicente-Serrano et al. (2010) developed SPEI, which is sensitive to long-term trends in temperature change. If such trends are absent, SPEI performs similarly to SPI. KBDI (Keetch and Byram 1968) o earlier considered temperature and has had wide application to wildfire monitoring. PAI (Pálfai 1991) considered groundwater in addition to these two indicators and has mainly been applied to basins within Hungary.

In addition to temperature and evapotranspiration, PDSI (Palmer 1965) also considers stream flow and soil moisture to give a more complete picture of the water balance (Niemeyer 2008 categorizes PDSI as a "comprehensive" drought index) and has remained popular despite criticism (cf. Sect. 4.1). Improvements include self-calibration capacity (Wells et al. 2004) and modifications to the evapotranspiration estimation methods replacing the original Thornthwaite method (Thornthwaite 1948) with other formulations.

Agricultural drought indices: Approaches to characterize agricultural drought mainly evolve around monitoring soil water balance and the subsequent deficit in the event of a drought. This applies to the seven non-remote-sensing agricultural drought indices considered in this work: RSM (e.g., Thornthwaite and Mather 1955), CMI (Palmer 1968), which is similar to PDSI however models short-term agricultural by considering moisture deficit only in the top 5 ft of soil column (Byun and Wilhite 1999; Narasimhan and Srinivasan 2005), and CSDI (Meyer et al. 1993) originally designed for corn and its variant for soybean (Meyer and Hubbard 1995). DT*x* (Matera et al. 2007) calculates the daily transpiration deficit (DT) for *x* days. DT*x* uses the CRITeRIA soil moisture balance model (Zinoni and Marletto 2003) with inputs including soil, crop, and weather conditions in addition to temperature anomalies, which affect evapotranspiration.

Increased spatial and temporal resolutions were sought in developing SMDI and ETDI (Narasimhan and Srinivasan 2005). This approach considers the soil component of the SWAT hydrologic model that has a resolution of 16 km^2 (compared to then 7 000 to 160 000 km^2 resolutions of SPI and PDSI). Within the top 2 m of the soil component, "soil profile", SMDI characterizes soil moisture deficit at varying depths: top 2 ft ($SMDI_2$), 4 ft ($SMDI_4$), and 6 ft ($SMDI_6$). $SMDI_2$ and ETDI (which considers evapotranspiration deficit) were suggested for short-term drought conditions monitoring and $SMDI_6$ for long-term monitoring.

Remote-sensing-based vegetation indices such as NDVI (Tucker 1979), EVI (Liu and Huete 1995), VegDRI (Brown et al. 2008), TCI (Kogan 1995), and NDWI (Gao 1996) are also used to monitor general vegetation state and health (Sivakumar et al. 2011).

Hydrological drought indices: This group of indices aims at providing a comprehensive characterization of delayed hydrologic impacts of drought. Earlier, the sophisticated PHDI (Palmer 1965) model considered precipitation, evapotranspiration, runoff, recharge, and soil moisture. The PDSI family of indice show ever lacked the snow component accumulation,

Table 5. Newer drought indices by category and date (MHA: combination).

Drought index and reference (s)	Type	Motive/requirements	Novelty and notes
Regional Streamflow Deficiency Index (RSDI) Stahl (2001)	H	Characterizing drought within each homogeneous region.	Uses flow duration curves and flows that exceed 90% of the time (Q90). Using the time series of streamflow, a deficiency index is computed which is used to identify homogenous regions using cluster analysis. RSDI is computed for each homogeneous region.
Aggregate Drought Index (ADI) Keyantash and Dracup (2004)	MHA	PDSI limitations including geographic biases, not sufficiently considering snowfall processes, and complex, empirical formulations based on the climate of US Midwestern states. SWSI does not consider evaporation and soil moisture.	ADI is a multivariate, aggregate index that inputs six hydrologic variables of precipitation, streamflow, reservoir storage, evapotranspiration, soil moisture and snow water content. Uses five to six variables. The first principle component (PC1) is normalized by its standard deviation.
Soil Moisture Deficit Index (SMDI) and **Evapotranspiration Deficit Index (ETDI)** Narasimhan and Srinivasan (2005)	A	By considering the spatial variability of hydrological parameters of soil type and land cover as well as meteorological parameters, it is possible to improve older indices such as SPI, PDSI, CMI and SWSI; the hydrologic system is better modeled and soil moisture deficit monitoring is possible at a finer resolution.	SMDI and ETDI use a high-resolution comprehensive hydrologic model that incorporates a crop growth model. Weekly values are calculated for different soil layers and depths. The difference is that SMDI considers soil moisture in its calculations while ETDI considers the water stress ratio: $\frac{PET-AET}{PET}$. Indices increase spatial (16 km^2) and temporal (weekly) resolution. Weekly values reflect short-term dry conditions, which is very helpful during plant growth phases.
Reconnaissance Drought Index (RDI) Tsakiris and Vangelis (2005)	M	Precipitation alone is inadequate and less realistic estimate of moisture deficit; the severity of drought is underestimated without PET. In addition, it is more difficult to correlate the damages from drought when PET is omitted from the equation. . Achieve a balance between two major meteorological parameters precipitation and potential evapotranspiration	RDI is more comprehensive than SPI. Advantages include: being physically based, RDI calculates the aggregated deficit between the evaporative demand of the atmosphere and precipitation; being flexible for different periods of time; better association with hydrological and agricultural droughts; RDI is also easy and simple to calculate using monthly precipitation and PET.
Standardized Precipitation Evapotranspiration Index (SPEI) Vicente-Serrano et al. (2010)	M	In an illustrative experiment, SPI could not identify the pattern of increase in the duration and magnitude of droughts resultant from higher temperatures. SPEI was required to overcome the shortcomings of SPI in addressing the consequences of climate change on drought behaviour.	Based on SPI, however incorporates temperature data. Considers water balance and evapotranspiration. Where there are no apparent temporal trends in temperature, SPEI is nearly equivalent toSPI or other precipitation drought index.
Modified Perpendicular Drought Index (MPDI) Ghulam et al. (2007*a*)	RS	The earlier developed PDI (Ghulam et al. 2007*b*) was found to lack accuracy on surfaces that are variable between bare soils and densely vegetated agricultural fields. For bare soils, both indices performed equally.	Ghulam et al. (2007*a*) added and additional term: “vegetation fraction” which considers soil moisture and vegetation growth. For nonflat topography with variable soil types and eco-systems MPDI outperforms PDI.
Normalized Multi-Band Drought Index (NMDI) Wang and Qu (2007)	RS	Enhancing the sensitivity of NDWI and NDII to drought severity.	Uses information from one NIR and two SWIR bands (MODIS bands 2, 6, and 7, respectively). Simultaneously extracts both vegetation and soil water content. Improved performance for dry soil and weakly vegetated areas. For dense vegetation performs similar to NWDI and NDII. Requires further study for application to moderately dense vegetation.
Vegetation Drought Response Index (VegDRI) Brown et al. (2008)	Agre	To characterize specific droughts; combines indices: NDVI, SPI, and PDSI	Provides near-real-time maps of drought severity and spatial extent; at 1 km resolution it is finer than the USDM, making it useful for local planning and mitigation
Hybrid Drought Index (HDI) (Karamouz et al. 2009)	Agre	Combined the SPI, SWSI and PDSI.	Better corresponds to various drought impacts.

Table 6. Additional drought indices and indicators (A: Agricultural, M: meteorological, Agre: Aggregate, H: Hydrological, RS: Remote-Sensing, ET: evapotranspiration, NIR: Near-Infrared, R: Red and SWIR: Short Wave Infrared).

Index/Indicator	Type	Source	Notes
Relative Soil Moisture (RSM)	A	Thornthwaite and Mather (1955)	RSM is calculated the water balance from various methods. Takes climate, soil, and crop variables including potential ET and precipitation; soil physical properties; and crop characteristics and crop management practices (Sivakumar et al. 2011). Reported in percentage.
Agricultural Drought Index (DTx)	A	Matera et al. (2007)	Uses a water balance model and crop transpiration to calculate an integrated transpiration deficit over a period of time.
Rainfall Anomaly Index (RAI)	M	Van-Rooy (1965)	Uses the average precipitation over weekly, monthly, or annual time periods to characterize relative drought. Relative drought is then ranked with respect to the 10 most severe droughts in the long-term record, based on which the drought is then assigned a magnitude (Wanders et al. 2010).
Bhalme and Mooly Drought Index (BMDI)	M	Bhalme and Mooley (1980)	Considers the percent departure of monthly or annual precipitation from its long-term means (Byun and Wilhite 1999).
Pálfai Aridity Index (PAI)	M	Pálfai (1991)	Characterizes drought severity using precipitation, temperature and ground water conditions data. Designed primarily for Hungarian and the Carpathian Basin climate conditions (UNFCCC 2002).
Drought Severity Index (DSI)	M	Bryant et al. (1992)	Uses the accumulated monthly deficit of precipitation in preceding months in a window of time, e.g., 3- or 6-month to characterize drought.
National Rainfall Index (NRI)	M	Gommes and Petrassi (1994)	Weights the total annual precipitation against its long-term average. Reveals patterns and abnormalities of yearly and inter-century precipitation on a continental scale (Byun and Wilhite 1999).
Drought Frequency Index (DFI)	M	González and Valdés (2006)	Uses the mean frequency of recurrence as the scale for the evaluating drought significance.
Weighted PDSI	H,M	Palmer (1965)	Uses PDSI of the current and the preceding week; efficient indicator of surface runoff drought (Vasiliades et al. 2011).
Groundwater Resource Index (GRI)	H	Mendicino et al. (2008)	Uses a simple distributed water balance model. Considers geo-lithological conditions that affect the summer hydrologic response to winter precipitation.
Water Balance Derived Drought Index	H	Vasiliades et al. (2011)	Uses the UTHBAL water balance model (Loukas et al. 2007) to simulate runoff. The index is then derived by normalizing and standardizing the synthetic runoff to the mean runoff.
Sperling Drought Index (SDI)	H	Droughtscore.com (2007)	Easily understandable measure (dry < 100 < wet); uses long-term precipitation patterns, groundwater, and reservoir levels, and the Palmer drought indices for drought characterization in longer time windows.
Vegetation Outlook (VegOut)	Agre	Tadesse and Wardlow (2007)	Combines climate information and RS observations of current vegetation conditions with oceanic index data and environmental biophysical information such as land cover type, irrigation status, soils, and ecological setting to provide a future outlook of general vegetation conditions.
Ratio Vegetation Index (RVI)	RS	Pearson and Miller (1972)	$\mathrm{RVI} = \frac{\mathrm{NIR}}{R}$
Weighted Difference Vegetation Index (WDVI)	RS	Clevers (1988); Richardson and Wiegand (1977)	$\mathrm{WDVI} = \mathrm{NIR} - \gamma R$. γ = the slope of the soil line (Qi et al. 1994)
Perpendicular Vegetation Index (PVI)	RS	Richardson and Wiegand (1977)	$\mathrm{PVI} = \sin(a)\mathrm{NIR} - \cos(a)R$. a = the angle between the soil line and the NIR (Ray 1994)
Difference Vegetation Index (DVI); Vegetation Index (VI)	RS	Lillesand and Kiefer (1987); Richardson and Everitt (1992)	$\mathrm{DVI} = \mathrm{NIR} - R$ (Ray 1994).
Leaf Water Content Index (LWCI)	RS	Hunt et al. (1987)	Uses remotely sensed leaf water content to classify plant health.
Soil Adjusted Vegetation Index (SAVI)	RS	Huete (1988)	$\mathrm{SAVI} = \frac{\mathrm{NIR} - R(1+L)}{(\mathrm{NIR}+R+L)}$ L = soil adjustment factor to account for first-order soil background variations (Qi et al. 1994)

Table 6 (*continued*).

Index/Indicator	Type	Source	Notes
Transformed SAVI (TSAVI1)	RS	Baret et al. (1989)	$\mathrm{TSAVI1} = \frac{\gamma(\mathrm{NIR}-\gamma)(R-i)}{R+\gamma\mathrm{NIR}-\gamma i}$. γ = soil line slope i = intercept (Qi et al. 1994)
Infrared Percentage Vegetation Index (IPVI)	RS	Crippen (1990)	Argued that the red subtraction in NDVI was unnecessary (Ray 1994). $\mathrm{IPVI} = \frac{\mathrm{NIR}}{\mathrm{NIR}+R} = \frac{\mathrm{NDVI}+1}{2}$
Second TSAVI (TSAVI2)	RS	Baret and Guyot (1991)	$\mathrm{TSAVI2} = \frac{\gamma(\mathrm{NIR}-\gamma R-i)}{\gamma\mathrm{NIR}+R-\gamma i+X(1+\gamma^2)}$ X = a factor to minimize the soil effects ($X = 0.08$); rest similar to TSAVI1.
Atmospherically Resistant Vegetation Index (ARVI)	RS	Kaufman and Tanre (1992)	First in the series of indices that have built-in atmospheric correction (Ray 1994). Replaced R in NDVI with RB, where: $\mathrm{RB} = R\text{–}\gamma\ (B\text{–}R)$ and γ is a correction parameter which was found to be efficiently applicable to all surfaces at $\gamma = 1$ and ARVI is thus: $\mathrm{ARVI} = \frac{\mathrm{NIR}-\mathrm{RB}}{\mathrm{NIR}+\mathrm{RB}}$
Modified Soil Adjusted Vegetation Index (MSAVI)	RS	Qi et al. (1994)	$\mathrm{MSAVI1} = \mathrm{SAVI} = \frac{\mathrm{NIR}-R\,(1+L)}{(\mathrm{NIR}+R+L)}$ $L = 1\text{–}2\gamma\mathrm{NDVI} \times \mathrm{WDVI}$ γ = the primary soil line parameter.
Second MSAVI (MSAVI2)	RS	Qi et al. (1994)	$\mathrm{MSAVI2} = \frac{2\mathrm{NIR}+1-\sqrt{(2\mathrm{NIR}+1)^2-8(\mathrm{NIR}-R)}}{2}$
Anomaly Vegetation Index (AVI)	RS	Chen et al. (1994)	Uses annual NDVI to study annual land surface dryness and vegetation dynamics.
Water Supplying VegetationIndex (WSVI)	RS	Chen et al. (1994)	Combines vegetation information with remotely sensed temperature data to detect drought.
Cubed Ratio Vegetation Index (CRVI) / (CVI)	RS	Thenkabail et al. (1994)	$\mathrm{CRVI} = \left(\frac{\mathrm{NIR}}{\mathrm{MIR}}\right)^3$ MIR = Landsat-5 Thematic Mapper mid-infrared.
Temperature-Vegetation Index (TVX)	RS	Lambin and Ehrlich (1995); Prihodko and Goward (1997)	TVX combines NDVI and LST as evidence for drought. The relationship of NDVI and LST has been subject of extended research (Qin et al. 2008). Lambin and Ehrlich (1995) express TVX as: $\mathrm{TVX} = \frac{\mathrm{LST}}{\mathrm{NDVI}}$ TVX is highly correlated with crop moisture content (Nemani et al. 1993) and near-surface soil moisture (Goetz 1997).
Modified NDVI (MNDVI); Enhanced Vegetation Index (EVI)	RS	Liu and Huete (1995)	NDVI applied to MODIS. Uses feedback loops to minimize both atmospheric and soil bias that is present in NDVI and other VIs.
Anomaly of NDVI	RS	Anyamba al. (2001)	Used NDVI departure patterns over Africa during the 1997/98 ENSO event to identify drought patterns.
Simple Ratio Water Index (SRWI)	RS	Zarco-Tejada and Ustin (2001)	Indicator of canopy water content. $\mathrm{SRWI} = \frac{R_{858.5}}{R_{1240}}$ $R_{858.5}$ = MODIS band 4 (858.5 nm) R_{1240} = MODIS band 5 (1240 nm).
Vegetation Temperature Condition Index (VTCI)	RS	Wang et al. (2001)	Uses NDVI and LST. Ranges between 0 and 1. For a specific NDVI value: NDVI_t, pixel VTCI is: $\mathrm{VTCI} = \frac{\mathrm{LST}_{\mathrm{NDVI}i.\max}-\mathrm{LST}_{\mathrm{NDVI}i}}{\mathrm{LST}_{\mathrm{NDVI}i.\max}-\mathrm{LST}_{\mathrm{NDVI}i.\min}}$ where $\mathrm{LST}_{\mathrm{NDVI}i.\max}$ and $\mathrm{LST}_{\mathrm{NDVI}i.\min}$ = maximum and minimum land surface temperatures of pixels in the study region $\mathrm{LST}_{\mathrm{NDVI}i}$ = land surface temperature of pixel.

Table 6 (*concluded*).

Index/Indicator	Type	Source	Notes
Global Vegetation Moisture Index (GVMI)	RS	Ceccato et al. (2002)	Retrieves the vegetation water content. $\text{GVMI} = \frac{(\text{NIR}_{rect}+0.1)-(\text{SWIR}+0.2)}{(\text{NIR}_{rect}+0.1)+(\text{SWIR}+0.2)}$
Standardized Vegetation Index (SVI)	RS	Peters et al. (2002)	Uses weekly NDVI to calculate the probability of the deviation of vegetation conditions from normal.
Temperature–Vegetation Dryness Index (TVDI)	RS	Sandholt et al. (2002)	Assesses soil moisture status. $\text{TVDI} = \frac{T_s - T_{s_{\min}}}{a + b\text{NDVI} - T_{s_{\min}}}$ $T_{s_{\min}}$ = the minimum surface temperature in the concept of $\frac{T_s}{\text{NDVI}}$ triangle space T_s = pixel's observed surface temperature *a* and *b* are parameters defining the dry edge, obtained from a linear fit for $T_{s_{\max}}$ (maximum surface temperature): $T_{s_{\max}} = a + b\,\text{NDVI}$
Cumulative Water Balance Index (CWBI)	RS	Dennison et al. (2003)	Measures regional drought stress by cumulatively summing the difference between precipitation and reference ET over a window of time.
Soil Water Index (SWI)	RS	Wagner et al. (2003)	Used the microwave C-band scatterometer data to derive a global soil moisture data set for years 1992–2000.
Land Surface Temperature (LST)	RS	Wan et al. (2004)	Since LST is sensitive to the drought, it was used as additional indicator along with NDVI.
Vegetation Condition Albedo Drought Index (VCADI)	RS	Ghulam et al. (2007*a*)	First in the series that was followed by PDI and MPDI (Ghulam et al. 2007*b*).
Perpendicular Drought Index (PDI)	RS	Ghulam et al. (2007*b*)	Second in the VCADI, PDI, and MPDI series (Ghulam et al. 2007*a*, 2007*b*).
Remote Sensing Drought Risk Index (RDRI)	RS	Liu et al. (2008)	Used cloud indexes over China as an indicator for drought.
Total Storage Deficit Index (TSDI)	RS	Yirdaw et al. (2008)	Calculates average terrestrial water storage from gravity measurements obtained from gravity recovery and climate experiment (GRACE) satellite mission.
Vegetation Water Stress Index (VWSI)	RS	Ghulam et al. (2008)	Uses NIR and shortwave infrared (SWIR) wavelengths. VWSI has a strong correlation with fuel moisture content which is indicative of wheat drought.
Scaled Drought Condition Index (SDCI)	RS	Rhee et al. (2010)	Current RS drought indices are for use mainly in arid regions. SDCI is designed for agricultural drought monitoring in both arid and humid regions. Combines NDVI and LST with precipitation data.
Vegetation Water Supply Index (VWSI)	RS	Cai et al. (2011)	Combines LST and NDVI. Performs more efficiently on agriculture fields with densely covered vegetation areas.

which led to the development of SWSI (Shafer and Dezman 1982), probably the most popular of this group. Later, RDI (Weghorst 1996) improved SWSI by incorporating temperature and hence calculated a variable water demand as input.

RSDI (Stahl 2001) bases its model on homogeneous drought-stricken regions that comprise several neighbouring low-flow gauging stations. RSDI first calculates the deficiency in streamflow compared with historic values and then uses cluster analysis to delineate the drought-stricken regions. Two later indices consider a water balance model: GRI (Mendicino et al. 2008) and Water Balance Derived Drought Index (Vasiliades et al. 2011). The former focuses on groundwater resources and uses geo-lithological conditions information in a distributed water balance model, while the latter uses a model that artificially simulates runoff for ungauged and low-data watersheds.

5.2 Expanding the remote-sensing capacity

New sensors and algorithms have constantly enabled the incorporation of improved remotely sensed information in drought characterization. New sensors have higher spatial resolution, a current shortcoming in drought indices products (Niemeyer 2008). Novel noise reduction algorithms and other atmosphere correction algorithms improve the thematic accuracy of remote-sensing datasets.

Remote-sensing indices are diverse and new indices are frequently proposed. While NDVI has remained popular, other indices such as VegDRI, VCI (Kogan 1990), TCI, and VHI (Kogan 1995) are currently operationally used (NDMC 2011; NOAA 2011). Traditionally used bands include near-infrared (NIR), red and short-wavelength infrared (SWIR). The Land Surface Temperature (LST) has been used as additional source along with NDVI to improve drought characterization accuracy (Cai et al. 2011; Lambin and Ehrlich 1995; Prihodko and Goward 1997; Rhee et al. 2010; Wan et al. 2004; Wang et al. 2001).

A comprehensive review of the performance of the large number of remote-sensing drought indices for different configurations can be helpful.

5.3 Aggregation of drought indices

Nonhybrid indices are mainly useful for particular places and specific objectives or applications and do not provide a comprehensive characterization of drought events. Combining drought indices has been increasingly discussed as a means to incorporate and more effectively exploit information that is readily available and proven to be useful in field-specific drought indices (Kallis 2008; Niemeyer 2008; Sivakumar et al. 2011). In follow-up to the Lincoln Declaration (WMO 2009), Sivakumar et al. (2011) recommended the creation of a new *composite* hydrologic drought index that would cover stream flow, precipitation, reservoir levels, snowpack, and groundwater levels. In general, hybrid drought indices can provide a stronger correlation with actual impacts sustained in the ground.

Most hybrid drought indices are comparatively recent, including the USDM (Svoboda et al. 2002) and VegDRI (Brown et al. 2008). VegDRI combines SPI and PDSI in addition to two NDVI-based indicators: Percent Average Seasonal Greenness (PASG) and Start of Season Anomaly (SOSA). Karamouz et al. (2009) combined the SPI, SWSI, and PDSI to develop the integrated HDI.

5.4 Climate change effects

The predicted nonstationarity in future climates (IPCC 2007) has instigated research for including future temporal patterns in drought characterization. The SPEI (Vicente-Serrano et al. 2010) accounts for the increase in the duration and magnitude of droughts resultant from higher temperatures. Additional research has been conducted for specific regions including Mpelasoka et al. (2008) for Australia and Dubrovsky et al. (2009) for the Czech Republic.

6. Summary

Drought characterization is essential for drought management operations. Using drought indices is a pragmatic way to assimilate large amounts of data into quantitative information that can be used in applications such as drought forecasting, declaring drought levels, contingency planning and impact assessment. This paper presented descriptions for 74 drought indices. It emphasized popular drought indices, however sufficient description was provided for the remaining drought indices. Using this comprehensive listing, a means is provided to compare drought indices within each group of application and to further study the trends in the development of drought indices in each category.

In conclusion, although some drought indices such as SPI and NDVI are popularly adopted, the variety of drought indices reflects a fundamental lack of universal definition and concepts, and different operational requirement. In addition to the variability in the types and applications of droughts (e.g., meteorological versus hydrological), the dissociation of drought indices with drought impacts has prompted calls for aggregate drought indices to cover more aspects and applications.

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