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DROUGHT INDICES USED TO REFLECT DIFFERENT DROUGHT CONDITIONS

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ABSTRACT
Shortage of food and water resources resulted from climatic crises has alarmed people around the world, in particular that the rainfed agriculture and vegetation of natural resources suffer from the irregular rainfall in most of the water years. The rainfall pattern possesses unique features: low intensity and high fluctuation. The persistent negative fluctuations of precipitation lead to drought characterized by different severity which imposes extensive damage on ecological and economic condition of the affected areas. The occurrence of drought is mainly a climatic phenomenon which cannot be eliminated. However, its effects can be reduced if actual spatio-temporal information related to crop status is available to the decision makers. Therefore, in this paper the comprehensive review of drought indices is presented and discussed enabling policy makers to manage drought effectively.

KEYWORDS: Drought, Rainfall, Drought indices.

INTRODUCTION

Drought is known to be the worst hydro-meteorological hazard of nature (Mishra and Desai, 2005). It is an abnormal and prolonged deficit in the available water and has a major impact on both natural and social hydrological resources (Wilhite, 2000; Tallaksen and Van Lanen, 2004; Mishra and Singh, 2010; Sheffield and Wood, 2011). It differs from other natural hazards by its slow accumulating process and its indefinite commencement and termination. Being a slow process although drought often fails to draw the attention of the world community, its impact persists even after ending of the event. A single definition of drought applicable to all spheres is difficult to formulate since concept, observational parameters and measurement procedures are different for experts of different fields. Beside, the concept of drought varies among regions of differing climates (Dracup *et al.*, 1980). The inter-annual variability in precipitation makes the arid region always at drought risk due to greater probability of below average precipitation (Smakhtin and Schipper 2008). According to the Centre for Research on the Epidemiology of Disasters (CRED), the drought causes large scale economical losses in a region and makes it more vulnerable for other hydro-meteorological disasters (Guha-Sapir *et al*., 2014). Obasi (1994) reported extreme meteorological events contribute approximately 85% of the natural disasters. 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. Three major drought types are identified that refer to different components of the hydrological cycle, namely, meteorological, soil moisture/agricultural and hydrological drought (Wilhite and Glantz, 1985). Depending on the type of drought the impacts on society and nature are different. This emphasizes the need to monitor drought throughout the hydrological cycle, to be able to pro-actively respond to all possible impacts. There are various methods and indices for drought analysis and they measure different drought-causative and drought-responsive parameters, and identify and classify drought accordingly. Bachmair *et al.* (2016) call for indices that are meaningful for drought impact assessments. Physical indices have been linked to drought impacts. For example, meteorological indices to drought impacts (Stagge *et al*., 2015; Blauhut *et al*., 2015, 2016) and forest fires (Gudmundsson *et al*., 2014), or to water scarcity indicators (Pedro-Monzonía *et al*., 2015). 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 (Niemeyer, 2008)

Drought assessment

Drought assessment is to understand the extent, causes and significance of drought which includes the spatial and temporal precipitation related data. Droughts were assessed with reference to nature of water deficits, mean periods, truncation levels and regionalization approaches (Dracup *et al.,* 1980). Over the years, however, various indices were developed to detect and monitor droughts. The effects of drought often accumulated slowly over a considerable period of time; they might linger for several years after the drought period ended. As a result, the onset and withdraw of a drought were difficult to determine, precisely, and that was why a drought was often referred to as a creeping phenomenon (Mishra *et al.,* 2007). After the various definitions of drought and their classification to confine the problem, many researchers attempted to assess drought severity. These studies were grouped under meteorological, hydrological and agricultural aspects, as classified by the National Commission on Agriculture (1976).

Meteorological drought assessment

Meteorological drought, in general, implies the deficiency of rainfall of such magnitude which would seriously affect the normal living of a society. Many indices and methods have been developed and are used to identify and determine the intensity of meteorological drought (Vogt Somma, 2000). Among them the standardised precipitation index *SPI* has received special attention in recent years since its introduction by McKee *et al*. (1993, 1995). It was applied to the analysis of regional droughts in Portugal (Paulo *et al.,* 2002; Alfonso 2005; Paulo, Pereira, 2006), in Crete (Tsakiris, Vangelis 2004), in Sicily (Bonaccorso *et al*., 2003), in Hungary (Szalai, Szinell, 2000; Szalai *et al*., 2000) and for the whole of Europe (Lloyd-Hughes, Saunders, 2002). It is widely recommended as a very simple and objective measure of meteorological drought (Vermes, 1998; Vermes *et al*., 2000; U.S. National Drought, 2014). . The widely used methods for meteorological drought assessment are the India Meteorological Department (IMD) method, the Herbst's method, Aridity Index, and the Palmer's Drought Severity Index (PDSI).

Hydrological drought assessment

Hydrological drought is understood with respect to low stream flows or little or no water availability. Innumeracy of literature is available for the stochastic characterisation of droughts using streamflow data (Gumbel, 1959; Chow, 1964; Huff, 1964; Yevjevi, 1967; Downer *et al*., 1967; Milan and Yevjevich, 1970; Joseph, 1970; Askew *et al*., 1971; Dyer, 1977; Rodda *et al*., 1978; Whipple, 1966; Zekai Sen, 1980; Chang, 1990). Chow (1988) suggested that the analysis of low stream flow was a suitable way of quantifying droughts. He found that during the periods of deficient precipitation, the deviation from normal conditions was greater for streamflow than for rainfall. He also suggested that low flow data must be specified in terms of magnitude of flow. Herbst *et al.* (1966), on the other, developed a method to assess the meteorological drought severity using rainfall data, which was applied by Mohan and Rangacharya (1991) for stream flow data. Yevjevich (1967) proposed a theory of runs which assesses the drought on the basis of deficiency of streamflow with respect to the long term mean value as the truncation level. Dracup (1980) assessed the drought based on the deficiency of streamflow with the long term median value as the truncation level.

Agricultural drought assessment

Agricultural drought results from the complex and nonlinear interactions between weather, soil, crop and human actions and hence, the assessment of the intensity of agricultural drought continues to be a challenging task for researchers, drought managers and policy makers. Unlike meteorological drought measured by rainfall data recorded by weather stations and the hydrological drought assessed by inflows into the surface water bodies measured through gauging points, assessment of agricultural drought is not accomplished by direct and quantitative measurements (Sastry *et al*., 1981). It requires the quantitative information related to rainfall, soil moisture, cropping pattern and crop condition along with their interactive effects in both spatio-temporal dimensions. Many indices and methods have been developed and are used to identify and determine the intensity of agricultural drought (Vogt, Somma 2000; Boken *et al*., 2005).

Drought indices

A drought index value is a single number used for decision-making. Drought indices are normally continuous functions of rainfall and/or temperature, river discharge or other measurable variable (Hayes, 2011). Rainfall data are widely used to calculate drought indices, because long-term rainfall records are often available. Rainfall data alone may not reflect the spectrum of drought related conditions, but they can serve as a pragmatic solution in datapoor regions. A brief description on drought indices which are grouped according to the surface of information used in their formulation such as meteorological, hydrological and agricultural is reviewed below.

Percent of Normal

These indices are simple, by definition, easy to calculate and are easily understood by a general audience. "Normal" may be, and usually is, set to a long-term mean or median precipitation value. It may be calculated for a day, a month, a season or a year and is considered to be 100%. The same percent of normal may have different specific impacts at different locations and, therefore, it is a bit of a simplistic measure of precipitation deficit. Also, what is normal may be perceived differently in different regions.

There are multiple definitions of a drought based on the percent or a proportion of normal. Bates (1935) suggested defining droughts in USA when annual precipitation is 75% of normal or monthly precipitation is 60% of normal. Banerji and Chabra (1964) considered severe drought conditions in the State of Andhra Pradesh, India to be coincident with a seasonal rainfall deficit of more than 50% (which means rainfall of less than 50% of normal). Ramdas (1950), also in India, considered a drought to arrive when actual rainfall for a week is half of normal or less. Generally, meteorological drought in India is defined when rainfall in a month or a season is less than 75% of its long-term mean. If the rainfall is 50-74% of the mean, a moderate drought event is assumed to occur, and when rainfall is less than 50% of its mean a severe drought occurs. A drought in South Africa are defined as periods with less than 70% of normal precipitation and becomes a disaster or severe drought when two consecutive seasons experience 70% of normal rainfall or less (Bruwer, 1990).

Dry Index (Id)

Dry index gives the relationship between temperature and precipitation of a region. It is given byId = 56 x log (120 x T)/P where T is the annual average temperature in °C and P is the annual average precipitation in mm. The index becomes positive for dry climatic regions and negative for moist climates. It is classified as arid extreme if Id > 72, arid moderate if Id is between 50-71 and arid mild if Id < 50 (Nagarajan, 2003).

Palmer Drought Severity Index (PDSI)

The most prominent index of meteorological drought in the United States is the Palmer Drought Severity Index (PDSI). The PDSI was created with the intent of "measuring the cumulative departure of moisture supply" (Palmer 1965). The PDSI is a dimensionless number typically ranging between 4 and -4, with negative quantities indicating a shortage of water. The PDSI calculates a series of water balance terms for a generic two-layer soil model, and fluctuations in the hypothetical moisture supply, depending upon observed meteorological conditions, are compared to a reference set of water balance terms. This comparison leads to computation of the dimensionless PDSI. Index values are calculated on an ongoing basis by the NCDC, and monthly PDSI values have been extended back to 1895 (NCDC 2000). Computation of the PDSI is complicated; it is ideally a standardized measure of moisture conditions across regions and time. However, Guttman *et al.* (1992) determined that routine climatological conditions tend to yield more severe PDSI measures in the Great Plains than other U.S. regions. The shortcomings of regional comparability—which the PDSI was designed to facilitate—are further detailed by Guttman *et al*. (1992). The PDSI is also imprecise in its treatment of all precipitation as rainfall, as snowfall may not be immediately available as water in the two-layer soil scheme (Hayes, 2000). On the positive side, the PDSI does factor in antecedent conditions and is calculable from basic data. But its empirical nature, coupled with the fact it was developed for U.S. agricultural regions, limits its broad applicability, and as a result the PDSI is not used internationally. Gibbs and Maher (1967) considered its application for Australia but instead recommended rainfall deciles. The classification criterion for this type of index is as shown in Table 1.

TABLE 1. Palmer Index Classification Criteria

Value	Condition
≥ 4.0	extremely wet
3.0 – 3.99	very wet
2.0 – 2.49	moderately wet
1.0 - 1.99	slightly wet
0.5 – 0.99	insipient wet spell
0.49 - -4.9	near normal
-0.5 - -0.99	insipient dry spell
-1.0 - -1.99	mild drought
-2.0 - -2.99	moderate drought
-3.0 - -3.99	severe drought
≤ -4.0	extreme drought

Standardized Precipitation Index

The Standardized Precipitation Index, SPI is an index based on the probability of precipitation for any time scale and is used by many drought planners due to its versatility. The advantages of the index include the fact that it can be computed for different time scales, can provide early warning of drought, help assess drought severity and is simpler compared to the Palmer index. The SPI has been in existence less than a decade, so it has not been broadly applied or tested, although it has been used with success in describing drought conditions in Texas and Oklahoma (Hayes *et al*., 1999; Hayes, 2000). Nonetheless, because the SPI relies upon widely measured precipitation data and can probabilistically describe precipitation shortages across any desired timescale, the NDMC and the Western Regional Climate Center (WRCC) advocate it over the traditional PDSI (Redmond, 2000).

It was developed on the basis that precipitation deficit has different impacts on ground water, reservoir storage, soil moisture and stream flow (McKee *et al*., 1993). Precipitation data are assumed to follow an incomplete gamma distribution (Redmond, 2000). The index was designed to quantify the precipitation deficit for multiple time scales that reflect the impact of drought on the availability of the different water resources. Soil moisture conditions respond to precipitation anomalies on a relatively short scale, while ground water, stream flow and reservoir storage reflect the longer-term precipitation anomalies. For these reasons, McKee *et al*. (1993) originally calculated the SPI for 3-, 6-, 12-, 24-, and 48-month time scales.

TABLE 2. Standardized precipitation index classification criteria

Value	Condition
≥ 2.0	extremely wet
1.5 –1.99	very wet
1.0 – 1.49	moderately wet
-0.99 - 0.99	near normal
-1.0 - -1.49	moderately dry
-1.5 - -1.99	severely dry
≤ -2.0	extremely dry

The calculation of the index for any location is based on the long-term precipitation record for a desired period. This long-term record is fitted to a probability distribution, which is then transformed into a normal distribution so that the mean SPI for the location and desired period is zero (Edwards & McKee, 1997). Positive SPI values indicate greater than median precipitation, while negative values indicate less than median precipitation. Since the

index is normalized, wetter and drier climates can be represented in the same way, and wet periods can also be monitored using the SPI. A drought event occurs any time the SPI is continuously negative and has intensity of -1.0 or less whilst it ends when the SPI becomes positive.
Each drought event, therefore, has a duration defined by its beginning and end, and intensity for each month that the event continues. The accumulated magnitude of drought (or drought magnitude) obtained by the positive sum of the SPI for all the months within a drought event. Because the SPI is standardized, these percentages are expected from a normal distribution of the SPI such that the 2.3% of SPI values within the extreme drought category is a percentage that is typically expected for an extreme event (Wilhite, 1995). This standardization allows the SPI to determine the rarity of drought occurrence, as well as the probability of the precipitation necessary to end the drought episode (McKee *et al*., 1993). The criteria as to when wet or drought conditions begin using the SPI index is shown in Table 3 (McKee *et al*., 1995).

TABLE 3. Phenomena reflected by specific-duration standardized precipitation indices (SPI) and their applications (NDMC 2006c)

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

Aridity Index (Ia)

Numerous numerical indices have been proposed to quantify the degree of dryness of a climate at a given location, and thus define climatic zones. Aridity indices were reviewed by Walton (1969) and Stadler (2005). Aridity indices have greater value for the tracking the effects of climate change on local water resources, if sufficiently accurate data are available for mapping local changes in the values of the indices over time. The simplest aridity index is based solely on precipitation. A commonly used rainfall-based definition is that an arid region receives less than 10-in or 250 mm of precipitation per year. This criterion for aridity was used by the Intergovernmental Panel on Climate Change (IPCC 2007). Semiarid regions are commonly defined by annual rainfalls between 10 and 20-in (250 and 500 mm).
The UNESCO (1979) aridity index (AI) is based on the ratio of annual precipitation (P) and potential evapotranspiration rates as follows:

$$\text{Aridity Index (Ia)} = \frac{P}{ETp}$$

Where, ETp is calculated using the Penman (1948) formula. UNESCO (1979) proposed a classification of climate zones based on AI index, in which arid regions are defined by an index of less than 0.20 (Table 4).

TABLE 4. UNESCO (1979) Aridity Classification

Classification	Aridity index
Hyperarid	AI <0.03
Arid	0.03<AI < 0.20
Semi-arid	0.20<AI < 0.50
Dry sub-humid	0.50<AI < 0.65

Deciles

The method of Deciles is one of the simplest meteorological drought indices. It is based on dividing the distribution of monthly record precipitation into 10% parts [Gibbs and Maher, 1967). This method requires an extended length of precipitation data record for accurate estimation. The precipitation totals for the preceding 3 months are ranked against climatologic records and if the sum falls within the lowest Decile of the historical distribution of 3-month totals, then the region is considered to be under drought conditions (Kininmonth et al, 2000). The drought ends when: (i) the precipitation measured during the past month already places the 3-month total in or above the fourth Decile, or (ii) the precipitation total for the past 3 months is in or above the eighth Decile (Tigkas et al, 2014). The five classes in which Deciles are grouped are mentioned in Table 5.

TABLE 5. Drought classification according to Deciles (Tigkas *et al*., 2014)

Decile class	Description
Deciles 1-2: lowest 20%	Much below normal
Deciles 3-4: next lowest 20%	Below normal
Deciles 5-6: middle 20%	Near normal
Deciles 7-8: next highest 20%	Above normal
Deciles 9-10: highest 20%	Much above normal

Crop moisture index

Palmer (1968) developed the Crop Moisture Index (CMI) to monitor short-term changes in moisture conditions affecting crops. The CMI is the sum of an evapotranspiration deficit (with respect to normal conditions) and soil water recharge. These terms are computed on a weekly basis using PDSI parameters, which consider the mean temperature, total precipitation, and soil moisture conditions from the previous week (Palmer 1968). The CMI can assess present conditions for crops, but it can rapidly vacillate and is a poor tool for monitoring long-term drought (Hayes 2000). For example, a rainstorm may briefly bring crops adequate moisture, even though an extended drought persists. The CMI also begins and ends each growing season near zero, which may be appropriate for botanical annuals, but not for tracking long-term drought. As a consequence, the assessment of agricultural drought is better suited to the related Palmer Z index (Karl 1986).

Normalised Difference Vegetation Index (NDVI)

In order to monitor the onset, duration and spatial extent of agricultural drought, long term NDVI is to be taken. This index is useful for estimation of biomass potential measuring leaf area index (LAI) and production pattern (Thenkabail *et al*., 2004). Over the years, NDVI has been successfully used by many researchers in different studies based on vegetation phenology, vegetation classification and mapping of continental land cover (Tucker *et al*., 1985; Tarpley *et al*., 1984). NDVI is suitable for monitoring drought, estimating healthy status of vegetation, crop growth conditions and crop yields (Kogan, 1987; Dabrowska-Zielinska *et al*., 2002; Singh *et al*., 2003). The basic concept of NDVI is based on the fact that internal mesophyll structure of healthy green leaves reflects Near-Infrared (NIR) radiation whereas the leaf chlorophyll and other pigments absorb a large proportion of the red visible (VIS) radiation. This function of internal leaf structure becomes reversed in case of unhealthy or water stressed vegetation.

$$NDVI = \frac{NIR - R}{NIR + R}$$

NDVI is calculated by the difference between reflectance in near infrared (NIR) and visible red (R) band of electromagnetic spectrum. The value of NDVI ranges between 1 and +1. It is found below 0.1 in the areas with barren rock, sand and snow cover whereas it may range from 0.6 to 0.8 in temperate and tropical rainforests. NDVI has been accepted as a popular index for monitoring agricultural drought (Son *et al*., 2012), estimating soil moisture (Xin *et al*., 2006; Chen *et al*., 2011) and vegetation condition (Singh *et al*., 2003). However, the utility of NDVI for studying vegetation and related issues may be constrained by several sources of error that usually occur due to atmospheric noise and many other reasons like satellite orbital drift, satellite change and sensor degradations (Kogan, 1995). Since weather related NDVI fluctuations cannot be detected easily, the ecological component must be separated from the impact of weather for estimating the actual condition of vegetation health.

Drought studies using remote sensing and GIS

The remote sensing community have defined drought specifically as a period of abnormal dry weather, which affects the vegetation cover (Heim, 2002).The traditional approaches for drought monitoring that uses ground-based data are laborious, difficult and time consuming (Prasad *et al*., 2007). Satellite measurements of the biosphere have gained their importance in various aspects of environmental monitoring including the drought monitoring. For drought monitoring, assessment and prediction, Remote sensing and GIS technologies are capable to cover the earth surface, better than traditional techniques. Several new approaches have been developed to extract information from past and real time remote sensing data for the purpose of drought studies. This remark was achieved only after the launch of AVHRR, on June 27, 1979 onboard obtained from National Oceanic and Atmospheric Administration (NOAA). There is an intense use of AVHRR to study in depth regarding the drought. Singh *et al.* (2003) have shown the integration of vegetation condition index and temperature condition index derived from data NOAA AVHRR, to monitor drought over entire India. Another study by Berhan *et al.* (2011) demonstrated the use of NDVI from NOAA AVHRR and Meteosat Second Generation (MSG) to monitor drought over Ethiopia. Gao *et al.* (2011) integrated LANDSAT TM/ETM+ derived temperature vegetation dryness index (TVDI) and regional water index (RWI) to assess drought over Shandong Province in China. Tao *et al.* (2011) represents the effective use of GIS for drought monitoring on Tongjinvallage of Dafang county located in Bijieprefecture of west Guizhou province. The Moderate-Resolution Imaging Spectro-radiometer (MODIS) presents a generational advancement over AVHRR. The narrower spectral bandwidths in MODIS for the red band and NIR band, which have increased sensitivity towards chlorophyll and water vapor absorption respectively, makes it more efficient for thematic applications (Huete *et al*., 2002). Drought is one of the most dominant causes for crop loss (Wilhite, 2002). Remote sensing is also helpful for Agricultural drought monitoring and assessment. Some of the approaches 8 developed by implementing Remote sensing data are established well enough for Agricultural drought identification and assessment as well. The assessment of drought probability for agricultural areas in Africa has been well shown by Rojas *et al*. (2011) by coarse resolution NDVI and VHI from NOAA AVHRR. Son *et al.* (2012) illustrated the use of monthly MODIS normalized difference vegetation index (NDVI) and land surface temperature (LST) data to monitor Agricultural drought along with integration to Tropical Rainfall Measuring Mission (TRMM) data. It is possible to use Remote sensing and GIS for Agricultural drought monitoring, assessment and prediction in areas with large extent. However, Remote sensing derived techniques solely are inefficient for generating a clear picture on drought studies. It needs to be integrated to other field variables like ground-based climate, hydrological, biophysical and surface datasets. Some unique approaches like collaboration of Remote sensing data to other fields have been also developed to take a step towards accuracy in assessment and prediction of Agricultural drought. Tadesse *et al.* (2005) integrated AVHRR NDVI 14 day dataset along with Meteorological drought indices from climate data and some biophysical parameters like land cover, eco-regions *etc*. to predict drought related vegetation stress over U.S. Central Plains. Uniting Remote sensing data with other variables is a significant approach to have potential outcomes.

CONCLUSION

Drought characterization is essential for drought management operations. Drought indices can be used in applications such as drought forecasting, declaring drought levels, contingency planning and impact assessment. It should be noted that various indices for different drought types are available and that different indices have strengths and weaknesses and that not a single index is superior to the rest in all circumstances but some indices may be better suited than others for certain applications. The Palmer Drought Severity Index, for instance, is widely to determine when to grant emergency drought assistance, but the Palmer is better when working with large areas of uniform topography. For other areas with mountainous terrain and with complex regional hydrological and microclimates. 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. The indices should, however, not be based on identical data. The choice of an index depends on the purpose of a study.

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