Indices for Drought Hazard mapping, Monitoring and Risk Assessment: Analysis of Existing Tools, Techniques and Approaches

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Abstract

Drought has always been cited as a scourge to mankind since biblical time and is still remaining as an unconquered ill. Drought means differently to different sections of the society and there is no common definition for drought. Drought Indices are used for mapping, monitory and risk assessment globally and their potential is well established. Different indices are used for drought assessments depending on the typology i.e. meteorological, hydrological and agricultural drought. Review of various methods shows that researchers and practitioners use combination of different indices to understand the impact of meteorological phenomena (i.e. low rainfall) on hydrological and agricultural systems. Socio economic impact of drought has also been mapped using indices developed based on mortality, number of persons affected, economic losses and other development indicators. Review of the existing tools, techniques and methods depicts that none of the indices are inherently superior or inferior to others. Selection of the indices shall be based on the purpose of the study, data availability and feasibility. Combination of indices gives better results in the case of drought due to the complexity of the phenomena.

Keywords: *Drought Indices, meteorological drought, hydrological drought, agricultural drought.*

Introduction

Since dawn of civilisation, drought has ever been viewed as a scourge to mankind and still remains a daunting challenge. Drought is an insidious hazard of nature and it ranks first among natural disasters throughout the world in terms of the number of persons directly affected (Hagman, 1984; Hewitt, 1997). Drought has different meaning to different sections of the society and there is no universal definition of drought. In lay

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terms, drought means shortage of moisture in the root zone for crops for a farmer, below average water levels in streams, reservoirs, ground water etc. for a hydrologists and water shortage which adversely affects the economy for an economist (Palmer, 1965). Drought has been defined by the international meteorological community as a "prolonged absence or marked deficiency of precipitation," a "deficiency of precipitation that results in water shortage for some activity or for some group" or a "period of abnormally dry weather sufficiently prolonged for the lack of precipitation to cause a serious hydrological imbalance" (World Meteorological Organization 1992; American Meteorological Society 1997). Drought differs from other natural hazards in several ways. It is a slow-onset natural hazard (Gillette, 1950). Droughts fall into four types i.e. meteorological, hydrological, agricultural and socio-economic (Palmer, 1965). An occurrence of drought is often triggered by deficiency in precipitation called as 'meteorological drought' (Wilhite and Glantz, 1985, 2005). It is considered as 'hydrological drought' when precipitation shortage affects the surface and ground water resources either due to precipitation shortage for a longer period (one to two years) or due to loss of storage or overexploitation (Meigh et al., 1999).

It is important that a drought by itself is not a disaster; the hazard or meteorological phenomena becomes a disaster by causing impacts on environmental and socio-economic systems. Therefore, the key vulnerabilities are embedded in the environmental and social dimensions. Socio-economic drought is rather the consequence of differential impact of drought on different groups within the population, depending on their access or entitlement to particular resources, such as land, and/or their access or entitlement to relief (Wilhite, 2005). Drought indices provide accurate results for identifying drought intensity, frequency, severity and spatial extent for monitoring and management studies. This helps in early drought detection and preparedness. This paper presents an analysis of various drought indices used globally with advantages and limitations. Besides this the paper gives an overview of vulnerability assessment methods specific to drought.

Indices for Hazard Mapping, Monitoring and Risk Assessment

Drought indices integrate data on rainfall, stream flow, water supply, vegetation indicators to present a brief picture of drought scenario. A drought index value has been found more useful than raw data for decision making, as it allows comparisons on temporal and spatial scales helping planners to prioritise and communicate information to diverse users (Wilhite, 2000). There are several studies on use of drought indices for monitoring drought situation and understanding the impacts of different type of droughts i.e., meteorological, hydrological and agricultural drought.

Although none of the 'major' drought indices for assessing meteorological drought is inherently superior or inferior to the other, these indices broadly help in depicting departure in precipitation during a given period of time from historically established norms. Some most commonly used drought indices are 'Percent of Normal', 'Standardised Precipitation Index', 'Palmer Drought Severity', 'Crop Moisture Index,' 'Surface Water Supply Index', 'Reclamation Drought Index' and Deciles. The first comprehensive drought index developed in the United States by Palmer, in 1965 called Palmer Drought Severity Index. The key limitation of this index is that Palmer values may lag emerging droughts by several months and less suited for mountainous land or areas of frequent climatic extremes. The index is complex and has an unspecified, built-in time scale that can be misleading (Hayes, 2000).

Standard Precipitation Index (SPI), developed by McKee et al. in 1993 for deriving index bases on precipitation is based on the probability of precipitation for any time scale. The SPI calculation 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 and McKee, 1997). Positive SPI values indicate greater than median precipitation, while negative values indicate less than median precipitation. Because SPI is normalised, wetter and drier climates can be represented in the same way, and wet periods can also be monitored using the SPI developed by McKee, et al. which can be computed for different time scales, and can provide early warning of drought and help assess drought severity, and is less complex than the Palmer values (Heim, 2002; Hayes, 2000). SPI can be computed for multiple time scales shorter for example 1-, 2- or 3-month, for early warning of drought and help assessing drought severity. Its spatial consistency makes the index suitable for comparisons between different locations in different climates and its probabilistic nature gives it historical context, which is well suited for decision-making. Although versatile, SPI is practically and numerically difficult to use if there are many grid points of many stations. It is based only on precipitation and thus, ratio of evapotranspiration potential is not taken into consideration.

Willeke et al. (1994) developed 'Percent by Normal' method for meteorological drought analysis. It is calculated by dividing actual precipitation by normal precipitation (typically considered to be a 30 year mean) and multiplying by 100 percent. This can be calculated for a variety of time scales. This method is quiet effective for comparing a single region or season. Major limitation of Percent by Normal precipitation is that the mean or average precipitation is often not the same as the median precipitation, which is the value exceeded by 50 percent of the precipitation occurrences in a long-term climate record. Precipitation on monthly or seasonal scales does not have a normal distribution. Use of the percent of normal comparison implies a normal distribution where the mean and median are considered to be the same. Precipitation records over time and location, varies considerably and there is no way to determine the frequency of the departures from normal or compare for different locations. It is difficult to establish link between the departure from normal and the impact due to the departure at a particular location using this index, and hence mitigating the risks of drought based on the departure from normal and form a plan of response (Willeke et al., 1994).

Gibbs & Maher (1967) used deciles of precipitation for assessing meteorological drought which provides an accurate statistical measurement of precipitation. Major limitation for using DI is that accurate calculations require a long rainfall data record. Drought monitoring has been using seven meteorological indices viz. Deciles Index (DI), Percent of Normal (PN), Standard Precipitation Index (SPI), China-Z Index (CZI), modified CZI (MCZI), Z-Score and Effective Drought Index (EDI) by Morid et al. (2006).

SWSI developed by Shafer and Dezman (1982), represents water supply conditions unique to each basin. Changing a data collection station requires that new algorithms be calculated, and the index is unique to each basin, which limits inter-basin comparisons. Groundwater Resource Index (GRI) can be used as a reliable tool useful in a multi-analysis approach for monitoring and forecasting drought conditions in Mediterranean climate (Mendicino et al., 2008). The Global Water System Project (GWSP) examines global water assessment indicators with links to poverty and food security, such as the Water Wealth Index (WWI) (Sullivan et al., 2006). The Water Wealth Index has five major components, viz., (i) agricultural productivity (ii) institutional capacity (iii) food security (iv) environment and (v) human health, which provides for scientifically-based, defendable process of aid prioritization as decision support for allocation of water-related aid.

Standardised Water-Level Index (SWI) developed based on mean seasonal water levels of 20 years (1984-2003) has been used to assess ground-water recharge deficit in Aravalli Region by Bhuiyan et al. (2006). SWI values of the wells were interpolated using spline interpolation technique in a GIS environment to generate SWI maps of the region. Vegetation drought indices like Vegetation Condition Index (VCI), Temperature Condition Index (TCI) and Vegetation Health Index (VHI) have been computed using NDVI values obtained from Global Vegetation Index (GVI) and thermal channel data of NOAA AVHRR satellite. The study revealed that negative SPI anomalies do not always correspond to drought and vice versa. SWI and VHI, however, represent the negative impact of adverse meteorological and hydrological conditions on water and vegetation respectively and hence presents better picture of drought than SPI for decision making. Similar results were found in a study on drought hazard and vulnerability mapping using SPI, VCI and SWI for Bundelkhand region, where drought events are more consistent with SWI and VCI values and not corresponding to lower value of SPI (Singh et al., 2013; Nair et al., 2013).

Mpelasoka et al. (2007) carried out a study based on comparison of two indices viz. rainfall deciles and Soil Water Moisture Index, to assess future drought events over Australia under global warming attributed to low and high greenhouse gas emission scenarios for 30-year period centred on 2030 and 2070). The results of the study based on both the indices are consistent with the drought events observed in Australia during 1970-2004. However comparison of the indices with projected drought scenarios shows that Soil-Moisture Deciles-based Drought Index is more relevant for resource management planning since it accounts for 'memory' of water status and meteorological drought indices alone are inadequate for reliable assessment of drought.

Remote sensing data and GIS technology has been used for mapping, monitoring, forecasting agricultural drought by space agencies, and other technical and scientific organisations worldwide. Tucker (1979), suggested Normalised Difference Vegetation Index (NDVI) as an index for monitoring vegetation vigor. Vegetation Condition Index (VCI) was used to understand the relative NDVI change, with respect to minimum historical NDVI value by Kogan (1995).

Hydrometeorological and Vegetation Indices for developing integrated systems for drought monitoring and assessment of water resources for Tuscany region of Italy have been carried out by Caparrini & Manzella (2009). Cross-evaluation of the SPI, Vegetation Indices from remote sensing (from MODIS and SEVIRIMSG), and outputs from the distributed hydrological model MOBIDIC, was used in real-time for water balance evaluation and hydrological forecast in the major basins of Tuscany.

Drought Risk and Vulnerability Analysis for Bundelkhand region of India using six indices has been carried out by Singh et al. (2013) and Nair et al. (2013). A range of indices for drought monitoring has been applied to analyse the nature of the drought and calculate the frequency and intensity of hydrological, meteorological, agricultural drought and composite drought risk. Percent by Normal, deciles of precipitation and SPI for meteorological drought, Standard Water Level Index (SWI) for Hydrological Drought, NDVI and VCI for agricultural drought were derived at district level. The response of the environmental system (i.e., in terms of hydrological and agricultural system) to meteorological drought has also been analysed using SWI, and VCI. The study helped in revealing the interrelationship between different drought types i.e., meteorological, hydrological and agricultural drought at district level for all the 13 districts of the region. Drought declaration incidences (by states) were consistent with periods of hydrological drought and agricultural drought and not actually with the hazard severity (i.e., metrological drought). This is evident from the example of Lalitpur district (in Madhya Pradesh) where extreme meteorological drought was reported during 2009 but there was no drought declaration.

Sadeghipour & Dracup (2007) analysed the regional frequency of multi-year hydrologic drought based on three parameters, viz. magnitude, severity and duration. A multivariate simulation model is used to estimate exceedance probabilities associated with regional drought maxima, taking advantage of random variations of droughts in both time and space. Regional extreme drought method developed is capable of generating a series of drought events which have not occurred historically, and are more severe than historic events.

Conceptual Framework, Tools, Techniques and Approaches for Vulnerability Assessment

Vulnerability is defined by various researchers as set of conditions, a measure of the resistance, and resilience against the impact of hazards or stresses (Baikie, 1994; Cutter, 1996; Wisner et .al, 2003; Adger, 2006). Cutter et al. (2003) developed a Social Vulnerability Index (SVI) based on 30 socio-economic variables, which contribute to reduction in a community's ability to prepare for, respond to, and recover from disasters for entire United States at county level. South Pacific Applied Geosciences Commission (SOPAC), the United Nations Environment Programme (UNEP) and partner institutions developed Environmental Vulnerability Index (EVI) to analyse the environmental vulnerabilities of Small Island Groups (Pratt et al., 2004). The EVI was one of the earliest efforts and examines vulnerability to environmental change and the index has been developed using 50 biophysical or natural environment (50 indicators) grouped into three sub-indices (hazards, 'resistance', damage), which excludes the human systems (Kaly et al., 2004). The EVI concept of vulnerability has been elaborated with environmental inputs as 'Environmental Entitlements' by Leach et al. (1999) similar to the Sen's entitlement framework (1982) and up-scaled from household sustenance to livelihood system level. 'Agricultural Water Crowding' was developed for analysis and mapping of vulnerability factor for water stress in terms of number of people sharing water (Sullivan et al., 2006).

Global mapping of drought patterns and impacts taking into account the meteorological and hydrological drought and social vulnerability was carried out by International Water Management Institute (Eriyagama et al., 2009). Drought Risk Index (DRI) developed by Zongxue et al. (1998) is an integrated drought risk index that combines precipitation, river discharge, reliability, resilience and vulnerability.

A methodology for assessing and mapping the composite vulnerability of agriculture to climate variability in the Indo Gangetic plains was demonstrated by Sehgal et al. (2013). Vulnerability of agriculture has been determined using three core components viz. hazard, sensitivity to climate change and adaptive capacity considering climatic and socio-economic factors and Agriculture Climate Vulnerability Index has been derived at district level for Indo-Gangetic plain covering five states of India.

Table 1: List of Indices used for drought hazard and vulnerability assessments

S. No.	Index	Advantages	Disadvantages	Developed by
1.	Palmer Drought Severity Index (PSDI)	The first comprehensive drought index developed in the United States	Palmer values may lag emerging droughts by several months; less well-suited for mountainous land or areas of frequent climatic extremes; complex, has an unspecified, built-in time scale that can be misleading	Palmer, 1965
2.	Percent by Normal	Quite effective for comparing a single region or season	Easily misunderstood, Can't be used for different regions	Willeke et al., 1994
3.	Decile of Precipitation	Provides an accurate statistical measurement of precipitation	Accurate calculations require a long climatic data record	Gibbs & Maher, 1967
4.	Crop Moisture Index (CMI)	Designed to monitor short-term moisture conditions	The CMI's rapid response to changing short-term conditions may provide misleading information about long-term conditions	Palmer, 1968

S. No.	Index	Advantages	Disadvantages	Developed by
5.	Standard Precipitation Index (SPI)	SPI can be computed for different time scales, can provide early warning of drought and help assess drought severity, and is less complex than PSDI	Values based on preliminary data may change	McKee, et al., Colorado State University, 1993
6.	The Surface Water Supply Index (SWSI)	Represents water supply conditions unique to each basin	Changing a data collection station or water management requires that new algorithms be calculated, and the index is unique to each basin, which limits inter basin comparisons	Shafer and Dezman, 1982
7.	Reclamation Drought Index (RDI)	RDI is calculated at a river basin level; it incorporates the supply components of precipitation, snowpack, streamflow, and reservoir levels	Index is unique to each basin, which limits inter basin comparisons	The Bureau of Reclamation
8.	Water Wealth Index (WWI)	Considers multiple indicators; useful in prioritising policy and management responses to the crisis facing freshwater resources	Complex and based on 18 indicators under 5 categories.	Sullivan et al., 2006

S. No.	Index	Advantages	Disadvantages	Developed by
9.	Standard Water Level Index (SWI)	Simple and easy to calculate since it is based on single type of data set and is useful in assessing areas of ground water deficit		Bhuiyan et al., 2006
10.	Normalised Difference Vegetation Index (NDVI)	Simplicity of the algorithm and its capacity to broadly distinguish vegetated areas from other surface types, the NDVI also has the advantage of compressing the size of the data to be manipulated by a factor 2 (or more), since it replaces the two spectral bands by a single new field; most successful in quickly identifying vegetated areas and their condition	NDVI is sensitive to a number of perturbing atmospheric factors. Over use of NDVI without ground checks for monitoring agricultural drought	Tucker, 1989
11.	Vegetation condition Index (VCI)	Useful for comparing the NDVI value of the year with long term mean	Derived from NDVI and hence beset with similar limitations	Kogan, 1995

S. No.	Index	Advantages	Disadvantages	Developed by
12.	Storage Capacity Index (SCI)	Capture adequacy of storage water capacity; storage capacity assessed in proportion to total renewable fresh water resources (surface and ground water)	Challenges in quantifying total renewable fresh water resources (surface and ground water)	Wilhite, 2005
13.	Storage Drought Duration Length Index (SLI)	Assessing the storage capacity in proportion to monthly water needs at country level	Based on monthly surface water withdrawals, ground water not taken into consideration	Used by Eriyagama et al. (2009)
14.	Socioeconomic Drought Vulnerability Index (SDVI)	Considering both physical and socio-economic factors	Complexity due to the integration of 3 other incidences: Employment Diversity Index, Income Diversity Index and Crop Range Index	Used by Eriyagama et al. (2009)
15.	Environmental Vulnerability Atlas (EVI)	EVI developed based on 50 biophysical indicators; rapid and standardised method for characterising vulnerability in an comprehensive way	Excludes the human systems; developed for Small Island Groups	South Pacific Applied Geoscience Commission (SOPAC), the United Nations Environment Programme (UNEP), 2005
16.	Drought Risk Index (DRI) is an integrated drought risk index	Combines precipitation, river discharge, reliability, resilience and vulnerability	Vulnerability based on the maximum drought intensity not socioecomic vulnerability	Zongxue et al., 1998

S. No.	Index	Advantages	Disadvantages	Developed by
17.	Agriculture Climate Vulnerability Index (Composite and Normalised Vulnerability Index)	Considered climatic, environmental, physical and socio economic factors; based on past data (and not climate projections)	Agriculture-focused although covering other socio economic and physical factors	Sehgal et al.(2013)
18.	Disaster Risk Index (4 natural disasters viz. earthquake, tropical cyclones, floods and drought	One of the first efforts towards DRI; based on past disaster data and simple index derived based on mortality and number of persons exposed	Only based on Mortality; other risks are not covered; huge gaps in historic data on disaster particularly the people died or indirectly affected by drought	Bureau of Crisis Prevention and Recovery, BCPR, UNDP (2004)
19.	DRI (Mortality and Economic Losses)	Mortality Risk Index, Risk of Economic Losses in proportion of GDP developed for 6 natural hazards	Gaps in historic data on disasters particularly the people died or indirectly affected by drought and economic losses. Not addressing livelihoods and environmental losses since they are not available in historic databases	Dilley et al. (2005)

Source: modified by the authors after Heim, 2002 & Eriyagama et al., 2009.

Jones & Preston (2011) reviewed various approaches to vulnerability mapping, their benefits and risks. A review of 45 studies on vulnerability assessment was carried out and categorized the assessments in 4 conceptual models viz. Risk Hazard Models (31%), Social Vulnerability Models (7%), PAR Models (51%) and Expanded Vulnerability (9%). Although tremendous advancements were made in the field of geospatial data availability and tools which enhanced the potential of vulnerability mapping, there are challenges associated with mapping vulnerability particularly social vulnerability. Review of studies revealed that results of the vulnerability assessments vary significantly within the same conceptual frame work for analysis. 'The over arching challenges associated with vulnerability mapping are absence of best practices, scales of assessment and data availability and management of uncertainties'. Four major indicators (availability, accessibility, utilisation & entitlement) and 14 variables were used for deriving composite Food Security Index (FSI) in the Food Security Atlas of Rural Uttar Pradesh and Rural Madhya Pradesh (IHD & WFP, 2008).

Cost and benefits of different mitigation strategies viz. insurance (non-structural interventions) and development of ground water irrigation (structural interventions) and its implications on rural livelihood was carried out by Mechler et al. (2008). Farming households mostly deriving income from subsistence farming were takes as unit of study. The studied revealed that a combination of insurance and irrigation i.e., the integrated approach offer more benefits at lower costs than single set of intervention.

Climate Change Vulnerability Index (CCVI) developed by Maplecroft (2011) identifies hotspots of climate risks based on 42 social, economic and environmental factors to assess national vulnerabilities across three core areas. The core areas include exposure to climate-related natural disasters and sea-level rise; human sensitivity, in terms of population patterns, development, natural resources, agricultural dependency and conflicts; and future vulnerability by considering the adaptive capacity of a country's government and infrastructure to combat climate change.

Conclusion

Different indices based on meteorological data, hydrological data, vegetation data and socio economic data etc. are used globally for hazard mapping, monitoring and risk assessment. Review of different indices for mapping and monitoring of drought revealed the potential of the indices and inherent limitations. Combination of more than one index gives better results due to the complexity of the phenomena of drought. It is important to understand the merits and limitations of the different tools, techniques and methods while using the indices. Selection of various indices for analysis shall be based on the purpose, availability of data and drought typology.

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