Journal of Hydrology 391 (2010) 202–216

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Review paper

A review of drought concepts

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ARTICLE INFO

Article history:
Received 2 February 2010
Received in revised form 7 July 2010
Accepted 9 July 2010

This manuscript was handled by Geoff Syme, Editor-in-Chief

Keywords:
Definitions
Drought indices
Groundwater droughts
Large scale climate indices
Paleoclimatic study for droughts

SUMMARY

Owing to the rise in water demand and looming climate change, recent years have witnessed much focus on global drought scenarios. As a natural hazard, drought is best characterized by multiple climatological and hydrological parameters. An understanding of the relationships between these two sets of parameters is necessary to develop measures for mitigating the impacts of droughts. Beginning with a discussion of drought definitions, this paper attempts to provide a review of fundamental concepts of drought, classification of droughts, drought indices, historical droughts using paleoclimatic studies, and the relation between droughts and large scale climate indices. Conclusions are drawn where gaps exist and more research needs to be focussed.

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doi:10.1016/j.jhydrol.2010.07.012

1. Introduction

Droughts are recognized as an environmental disaster and have attracted the attention of environmentalists, ecologists, hydrologists, meteorologists, geologists and agricultural scientists. Droughts occur in virtually all climatic zones, such as high as well as low rainfall areas and are mostly related to the reduction in the amount of precipitation received over an extended period of time, such as a season or a year. Temperatures; high winds; low relative humidity; timing and characteristics of rains, including distribution of rainy days during crop growing seasons, intensity and duration of rain, and onset and termination, play a significant role in the occurrence of droughts. In contrast to aridity, which is a permanent feature of climate and is restricted to low rainfall areas (Wilhite, 1992), a drought is a temporary aberration. Often there is confusion between a heat wave and a drought. Chang and Wallace (1987) have emphasized the distinction between heat wave and drought, noting that a typical time scale associated with a heat wave is on the order of a week, while a drought may persist for months or even years. The combination of a heat wave and a drought has dire socio-economic consequences.

Due to the growth of population and expansion of agricultural, energy and industrial sectors, the demand for water has increased manyfold and even water scarcity has been occurring almost every year in many parts of the world. Other factors, such as climate change and contamination of water supplies, have further contributed to the water scarcity. In recent years, floods and droughts have been experienced with higher peaks and severity levels. The period between extreme events seems to have become shorter in certain regions. Lettenmaier et al. (1996) and Aswathanarayana (2001) have made references to this change in the occurrence of extreme hydrologic events.

Droughts impact both surface and groundwater resources and can lead to reduced water supply, deteriorated water quality, crop failure, reduced range productivity, diminished power generation, disturbed riparian habitats, and suspended recreation activities, as well as affect a host of economic and social activities (Riebsame et al., 1991). Droughts also affect water quality, as moderate climate fluctuations alter hydrologic regimes that have substantial effects on the lake chemistry (Webster et al., 1996). Sediment, organic matter, and nutrients are transported to surface waters by runoff, a pathway that is interrupted during droughts.

Droughts are of great importance in the planning and management of water resources. The objective of this study is to review fundamental aspects as well as some recent developments that have taken place in drought hydrology. The paper is organized as follows. With a brief introduction in Section 1, Section 2 presents an overview of the necessity for drought research, followed by a discussion on drought as natural hazards in Section 3 and drought definitions in Section 4. Section 5 reviews drought indices along with their limitations, and Section 6 reviews methodologies to understand historical droughts using palaeoclimatology, followed by a discussion on the relationship between droughts with large scale climate indices in Section 7. The review is concluded in Section 8.

2. Need for drought research

Assessment of droughts is of primary importance for freshwater planning and management. This requires understanding historical droughts in the region as well as impacts of droughts during their occurrences. Therefore, understanding different concepts of droughts will be helpful for developing models to investigate different drought properties, which is beyond the scope of the present discussion. The motivation for current discussion is due to the developments in global drought scenarios during recent years, which are discussed in what follows.

2.1. Impact of climate change on droughts

Climate change is now recognized as one of the major threats for the planet earth in the twenty-first century. According to the Intergovernmental Panel on Climate Change (IPCC) report (IPCC, 2007), instrumental observations over the past 157 years show that temperatures at the surface have risen globally, with significant regional variations. For the global average, warming in the last (20th) century has occurred in two phases, from the 1910s to the 1940s (0.35 °C), and more strongly from the 1970s to the present (0.55 °C). An increasing rate of warming has taken place over the last 25 years, and 11 of the 12 warmest years on record have occurred in the past 12 years. In general, this warming intensifies the global hydrological cycle (e.g., Milly et al., 2002) and it is well established that the earth's mean surface temperature has been increasing following the last glacial maximum 21,000 years ago

(Clark et al., 1999), thus increasing the globally averaged precipitation, evaporation, and runoff. The consequence of global warming is not the change in the averages but the overall increase of extreme events. Among the extreme meteorological events, droughts are possibly the most slowly developing ones, that often have the longest duration, and at the moment the least predictability among all atmospheric hazards. Studies on how climate change will affect various ecosystems have been conducted as an international effort on many fronts. Most of these studies address the effect in terms of changes in discharge caused by changed precipitation and temperature, the effects varying widely with the adopted scenarios and catchment type (e.g., Gleick, 1987; Karl and Riebsame, 1989; Lettenmaier and Gan, 1990; Panagoulia, 1992).

However, unlike floods analyzes of changes in drought characteristics due to climate change impacts have not been explored fully. Amongst recent studies on understanding drought impacts, Szep et al. (2005) have found that local soil moisture conditions in East Hungary became drier in the 20th century, parallel to the hemispherical changes. Andreadis and Lettenmaier (2006) have examined agricultural and hydrological droughts in USA, and have observed that droughts have, for the most part, become shorter, less frequent, and cover a smaller portion of the country over the last century except southwest and parts of the interior of the west, where trends in drought characteristics, that are mostly opposite to those for the rest of the country, especially in the case of drought duration and severity, have increased. In another study, Mishra and Singh (2009) highlighted the changes in drought severity-area-frequency due to climate change scenarios and compared with historical droughts for Kansabati River basin in India.

It is now accepted that droughts in future pose a threat to climate sensitive economic sectors, specifically agriculture, and have therefore necessitated the assessment of potential impacts of climate change on crop production at various scales. This will help develop measures to reduce agricultural vulnerability and thereby secure livelihoods of those who depend on agriculture. The following section discusses how droughts have affected different continents around the globe during recent decades to draw attention to the necessity for understanding droughts.

2.2. Impact of droughts around the globe during recent decades

Droughts produce a complex web of impacts that span many sectors of the society, including economy and may reach well beyond the area experiencing a drought. They are a widespread phenomenon (Kogan, 1997), since about half of the earth's terrestrial surfaces are susceptible to them. More importantly, almost all of the major agricultural lands are located there (USDA, 1994). Of all the 20th century natural hazards, droughts have had the greatest detrimental impact (Bruce, 1994; Obasi, 1994). In recent years, large scale intensive droughts have been observed on all continents, affecting large areas in Europe, Africa, Asia, Australia, South America, Central America, and North America (Le Comte, 1995; Le Comte, 1994) and high economic and social costs have led to increasing attention to droughts (Downing and Bakker, 2000). The impact of droughts on different continents around the globe is now discussed.

2.2.1. North America

During the last two decades, the impacts of droughts in the United States have increased significantly with an increased number of droughts or an increase in their severity (Wilhite and Hayes, 1998; Changnon et al., 2000). For example, the impact of the 1988 large-area drought on the US economy has been estimated at $40 billion, which is 2–3 times the estimated loss caused by the 1989 San Francisco earthquake (Riebsame et al., 1990). Based on the data available from the National Climatic Data Center, USA (2002), nearly 10% of the total land area of the United States experienced either severe or extreme droughts at any given time during the last century. Over the years 1980 to 2003, in the United States as a whole, droughts (and associated heat waves) accounted for 10 of the 58 weather-related disasters (Ross and Lott, 2003). Droughts (17.2% of the total) alone accounted for $144 billion (41.2%) of the estimated $349 billion total cost of all weather-related disasters (Ross and Lott, 2003). Hence, in economic terms alone droughts are costliest natural disasters to strike the United States (Cook et al., 2007).

Although most regions of Canada have experienced droughts, the Canadian Prairies (and to a lesser extent, interior British Columbia) are more susceptible mainly due to their high variability of precipitation in both time and space (Environment Canada, 2004). During the past two centuries, at least 40 long-duration droughts occurred in Western Canada. In southern regions of Alberta, Saskatchewan, and Manitoba, multi-year droughts were observed in the 1890s, 1930s, and 1980s (Phillips, 1990; Wheaton, 2000). Droughts in Eastern Canada are usually shorter, smaller in area, less frequent, and less intense; nonetheless, some major droughts occurred during the 20th century. Over much of the Prairies, several consecutive seasons of below average precipitation have led to one of the most severe prairie droughts on record, devastating many water-dependent activities in 2001 and 2002 (Environment Canada, 2004). In 2001, the aggregate level of the Great Lakes plunged to their lowest points in more than 30 years, with Lake Superior and Lake Huron displaying near record lows (Mitchell, 2002).

2.2.2. Europe

The drought situation in many European regions has already become more severe (Demuth and Stahl, 2001). For example, Lehner et al. (2006) presented a continental, integrated analysis of possible impacts of global change (here defined as climate and water use change) on future flood and drought frequencies for the selected study area of Europe. The global integrated water model WaterGAP was evaluated regarding its capability to simulate high and low flow regimes, which was then applied to calculate relative changes in flood and drought frequencies. The results indicated large 'critical regions' for which significant changes in flood or drought risks might be expected under proposed global change scenarios. The regions most prone to a rise in flood frequencies are northern to north-Eastern Europe, while southern and South-eastern Europe shows significant increases in drought frequencies. There will be an increase in the average precipitation and its variability is expected for northern regions, suggesting higher flood risks, while less rainfall, prolonged dry spells and increased evaporation may increase the frequency of droughts in southern areas (Watson et al., 1997; EEA, 1999; Voss et al., 2002). Because of their large scale characteristics, droughts should be studied within a regional context (Demuth and Stahl, 2001; Tallaksen, 2000; Mishra and Singh, 2009).

It is observed that during the past 30 years, Europe has been affected by a number of major drought events, most notably in 1976 (Northern and Western Europe), 1989 (most of Europe), 1991 (most of Europe), and more recently, the prolonged drought over large parts of Europe associated with the summer heat wave in 2003 (Feyen and Dankers, 2009). The most serious drought in the Iberian Peninsula in 60 years occurred in 2005, reducing overall EU cereal yields by an estimated ten per cent (United Nations Environment Programme, 2006). Since 1991, the yearly average economic impact of droughts in Europe has been €5.3 billion, with the economic damage of the 2003 drought in Europe amounting to at least €8.7 billion (European Communities, 2007).

2.2.3. Asia

According to a recent IPCC study, production of rice, maize and wheat in the past few decades has declined in many parts of Asia due to increasing water stress, arising partly from increasing temperature, increasing frequency of El Niño events and reduction in the number of rainy days (Bates et al., 2008). For examples, during 1999–2000, up to 60 million people in Central and Southwest Asia were affected by a persistent multi-year drought, one of the largest from a global perspective IRI, 2001), with Iran, Afghanistan, Western Pakistan, Tajikistan, Uzbekistan and Turkmenistan experiencing the most severe impacts.

In another example, frequent severe droughts in 1997, 1999 to 2002 in many areas of northern China caused large economic and societal losses (Zhang, 2003). In 2000, agricultural areas affected by droughts were estimated to exceed 40 million hectares. Because of droughts, water shortage, desertification, and dust storms accompanied the drying climate in both rural and urban areas. For instance, during 1972–1997, there were 20 years during which the Yellow River experienced drying-up (zero streamflow) episodes, and the earlier start time and longer periods of the drying-up have become more frequent since the early 1990s. The severe drought of 1997 in northern China resulted in a period of 226 days with no streamflow in the Yellow River, which is the longest drying-up duration on record. It is also observed that there has been an increased risk of droughts since the late 1970s, as global warming progresses and produces both higher temperatures and increased drying (Zou et al., 2005; Dai et al., 2004).

India is amongst the most vulnerable drought-prone countries in the world; a drought has been reported at least once in every three years in the last five decades. What is of concern is its increasing frequency. Since the mid-nineties, prolonged and widespread droughts have occurred in consecutive years, while the frequency of droughts has also increased in recent times (FAO, 2002; World Bank, 2003).

2.2.4. Australia

Drought is a recurring theme in Australia, with the most recent, the so called 'millennium' drought, now having lasted for almost a decade (Bond et al., 2008). This severe drought has affected most of Southern and Eastern Australia and is regarded as one of the worst in the region since European settlement (Murphy and Timbal, 2007), with many rivers experiencing record low flows over this period—in some cases almost 40% below previous records (Murray-Darling Basin Commission, 2007).

For example, the Australian Bureau of Agriculture and Resource Economics estimates that the 2006 drought reduced the national winter cereal crop by 36% and cost rural Australia around AUD $3.5 billion, leaving many farmers in financial crisis (Wong et al., 2009).

2.2.5. Africa

Since the late 1960s, the Sahel—a semiarid region in West Africa between the Sahara desert and the Guinea coast rainforest—has experienced a drought of unprecedented severity in recorded history. The drought has had a devastating impact on this ecologically vulnerable region and was a major impetus for the establishment of the United Nations Convention on Combating Desertification and Drought (Zeng, 2003). While the frequency of droughts in the region is thought to have increased from the end of the 19th century, three long droughts have dramatic environmental and societal effects upon the Sahel nations. Famine followed severe droughts in the 1910s, the 1940s, and the 1960s, 1970s and 1980s, although a partial recovery occurred from 1975–1980. While at least one particularly severe drought has been confirmed in each century since the 1600s, the frequency and severity of the recent Sahelian drought stands out. Famine and dislocation on a massive scale—from 1968 to 1974 and again in the early and mid 1980s—was blamed on two spikes in the severity of the 1960–1980s drought period (Batterbury and Warren, 2001).

3. Droughts as natural hazards

A natural hazard is a threat of a naturally occurring event that will have a negative effect on people or the environment and drought is a kind of natural hazard which is further aggravated by growing water demand. The reasons for the occurrence of droughts are complex, because they are dependent not only on the atmosphere but also on the hydrologic processes which feed moisture to the atmosphere. Once dry hydrologic conditions are established the positive feedback mechanism of droughts sets in, where the moisture depletion from upper soil layers decreases evapotranspiration rates, which, in turn, lessen the atmospheric relative humidity. The lesser the relative humidity the less probable the rainfall becomes, as it will be harder to reach saturation conditions for a regular low pressure system over the region. Only disturbances which carry enough moisture from outside the dry region will be able to produce sufficient rainfall to end drought conditions (Bravar and Kavvas, 1991).

Droughts rank first among all natural hazards when measured in terms of the number of people affected (Obasi, 1994; Hewitt, 1997; Wilhite, 2000b). Although as a natural hazard, droughts differ from other natural hazards in several ways (Wilhite, 2000a). First, the onset and the end of a drought are difficult to determine, the impacts of a drought increase slowly, often accumulate over a considerable period and may linger for years after termination. Therefore, a drought is often referred to as a creeping phenomenon. Second, it is difficult to define a drought which leads to confusion for not having a universal definition of drought. Third, drought impacts are non-structural and spread over large geographical areas than damages that may result from other natural hazards. In contrast to floods, hurricanes, earthquakes, and tornadoes a drought affects water bodies of water resources structures and it seldom results in structural damage. For this reason, the quantification of the impact and the provision for relief are far more difficult for droughts than for other natural hazards (Wilhite, 2000a). Fourth, human activities can directly trigger a drought unlike other natural hazards, with exacerbating factors such as overfarming, excessive irrigation, deforestation, over-exploiting available water, and erosion, adversely impacting the ability of the land to capture and hold water.

Bryant (1991) ranked hazard events based on their characteristics and impacts. Key hazard characteristics used for ranking included the degree of severity, the length of event, total areal extent, total loss of life, total economic loss, social effect, long-term impact, suddenness, and occurrence of associated hazards. It was found that drought stood first based on most of the hazard characteristics. Other natural hazards, which followed droughts in terms of their rank, are tropical cyclones, regional floods, earthquakes, and volcanoes.

4. Drought definitions

Differences in hydrometeorlogical variables and socioeconomic factors as well as the stochastic nature of water demands in different regions around the world have become an obstacle to having a precise definition of drought. Yevjevich (1967) stated that widely diverse views of drought definitions are one of the principal obstacles to investigations of droughts. When defining a drought it is important to distinguish between conceptual and operational definitions (Wilhite and Glantz, 1987). Conceptual definitions – those stated in relative terms (e.g., a drought is a long, dry period), where as operational definitions, on the other hand, attempt to identify the onset, severity, and termination of drought periods. Generally operationally defined droughts can be used to analyze drought frequency, severity, and duration for a given return period (for example, Mishra and Singh, 2009). Some of the commonly used definitions are: (i) The World Meteorological Organization (WMO, 1986) defines 'drought means a sustained, extended deficiency in precipitation.' (ii) The UN Convention to Combat Drought and Desertification (UN Secretariat General, 1994) defines 'drought means the naturally occurring phenomenon that exists when precipitation has been significantly below normal recorded levels, causing serious hydrological imbalances that adversely affect land resource production systems.' (iii) The Food and Agriculture Organization (FAO, 1983) of the United Nations defines a drought hazard as 'the percentage of years when crops fail from the lack of moisture.' (iv) The encyclopedia of climate and weather (Schneider, 1996) defines a drought as 'an extended period – a season, a year, or several years – of deficient rainfall relative to the statistical multi-year mean for a region.' (v) Gumbel (1963) defined a 'drought as the smallest annual value of daily streamflow.' (vi) Palmer (1965) described a 'drought as a significant deviation from the normal hydrologic conditions of an area.' (vii) Linseley et al. (1959) defined 'drought as a sustained period of time without significant rainfall.' However, drought definitions vary, depending on the variable used to describe the drought. Hence, drought definitions can be classified into different categories which are discussed below.

4.1. Classification of droughts

The droughts are generally classified into four categories (Wilhite and Glantz, 1985; American Meteorological Society, 2004), which include:

(i) Meteorological drought is defined as a lack of precipitation over a region for a period of time. Precipitation has been commonly used for meteorological drought analysis (Pinkeye, 1966; Santos, 1983; Chang, 1991; Eltahir, 1992). Considering drought as precipitation deficit with respect to average values (Gibbs, 1975), several studies have analyzed droughts using monthly precipitation data. Other approaches analyze drought duration and intensity in relation to cumulative precipitation shortages (Chang and Kleopa, 1991; Estrela et al., 2000).

(ii) Hydrological drought is related to a period with inadequate surface and subsurface water resources for established water uses of a given water resources management system. Streamflow data have been widely applied for hydrologic drought analysis (Dracup et al., 1980; Sen, 1980; Zelenhasic and Salvai, 1987; Chang and Stenson, 1990; Frick et al., 1990; Mohan and Rangacharya, 1991; Clausen and Pearson, 1995). From regression analyzes relating droughts in streamflow to catchment properties, it is found that geology is one of the main factors influencing hydrological droughts (Zecharias and Brutsaert, 1988; Vogel and Kroll, 1992).

(iii) Agricultural drought, usually, refers to a period with declining soil moisture and consequent crop failure without any reference to surface water resources. A decline of soil moisture depends on several factors which affect meteorological and hydrological droughts along with differences between actual evapotranspiration and potential evapotranspiration. Plant water demand depends on prevailing weather conditions, biological characteristics of the specific plant and stage of growth, and the physical and biological properties of soil. Several drought indices, based on a combination of precipitation, temperature and soil moisture, have been derived to study agricultural droughts.

(iv) Socio-economic drought is associated with failure of water resources systems to meet water demands and thus associating droughts with supply of and demand for an economic good (water) (AMS, 2004). Socio-economic drought occurs when the demand for an economic good exceeds supply as a result of a weather-related shortfall in water supply.

Several studies have discussed these four types of droughts, however it will be useful and important to introduce ground water drought as a type of drought which has not been included in the classification of droughts. To date, little research has been done on the occurrence and propagation of droughts in groundwater. The following section discusses ground water drought in more detail as this can be treated as a new type of drought.

4.2. Ground water drought

When groundwater systems are affected by droughts, first groundwater recharge and later groundwater levels and groundwater discharge decrease. Such droughts are called groundwater droughts and generally occur on a time scale of months to years (van Lanen and Peters, 2000). For groundwater, the total amount of water available is difficult to define. Even if it can be defined, in most groundwater systems, negative impacts of storage depletion can be felt, long before the total storage is depleted (van Lanen and Peters, 2000; Calow et al., 1999). Therefore, most often a groundwater drought is defined by the decrease of groundwater level (Chang and Teoh, 1995; Eltahir and Yeh, 1999). However, groundwater storage, or groundwater recharge (Marsh et al., 1994) or discharge (Peters et al., 2001) can be and has also been used to define or quantify a groundwater drought.

4.2.1. Propagation of groundwater drought

Like other types of natural droughts, groundwater droughts are caused by low precipitation possibly in combination with high evapotranspiration. A lack of precipitation causes low soil moisture content which, in turn, causes low groundwater recharge. The resulting shortage in precipitation propagates through the hydrological system, causing a drought in different segments of the hydrological system (unsaturated zone, saturated groundwater, surface water). This means that the response of groundwater systems to droughts and their performance under drought conditions become increasingly important (White et al., 1999). Another cause of a groundwater drought is abstraction, which may enhance naturally occurring droughts, and overexploitation may create a groundwater drought (Acreman et al., 2000; van Lanen and Peters, 2000).

The consequences of groundwater droughts are diverse. The direct effects are lower groundwater heads and a decrease in groundwater flow to riparian areas, springs and streams. For shallow groundwater, capillary rise to the vegetation will decrease, which may affect wetlands and crop yield negatively. Also well yields may decrease and shallow wells may even dry up (Calow et al., 1999). Because of the shortcomings in the conventional concept of a groundwater drought, now-a-days the concept of a groundwater drought as a result of the temporal variability of the weather is used increasingly (Chang and Teoh, 1995; Eltahir and Yeh, 1999).

Finally, for deriving drought definitions, the important parameters are the type of drought or nature of deficit which includes hydrometeorlogical variables, such as streamflow, precipitation in addition to soil moisture and groundwater levels. For identifying short or long-term droughts, the temporal scale varies from month to years. Different truncation levels can be used to identify severity of droughts, and commonly used truncation levels include mean, median and percentiles. Also, droughts can be differentiated based on a spatial scale, which can be on a local scale regional or even national scale.

It will now be useful to understand drought indices and their limitations which are generally used to investigate droughts in a region.

5. Drought indices

Several drought indices have been derived in recent decades. Commonly, a drought index is a prime variable for assessing the effect of a drought and defining different drought parameters, which include intensity, duration, severity and spatial extent. It should be noted that a drought variable should be able to quantify the drought for different time scales for which a long time series is essential. The most commonly used time scale for drought analysis is a year, followed by a month. Although the yearly time scale is long, it can also be used to abstract information on the regional behavior of droughts. The monthly time scale seems to be more appropriate for monitoring the effects of a drought in situations related to agriculture, water supply and ground water abstractions (Panu and Sharma, 2002). A time series of drought indices provides a framework for evaluating drought parameters of interest.

A number of different indices have been developed to quantify a drought, each with its own strengths and weaknesses. They include the Palmer drought severity index (PDSI; Palmer 1965), rainfall anomaly index (RAI; van Rooy, 1965), deciles (Gibbs and Maher, 1967), crop moisture index (CMI; Palmer, 1968), Bhalme and Mooly drought index (BMDI; Bhalme and Mooley, 1980), surface water supply index (SWSI; Shafer and Dezman, 1982), national rainfall index (NRI; Gommes and Petrassi, 1994), standardized precipitation index (SPI; McKee et al., 1993, 1995), and reclamation drought index (RDI; Weghorst, 1996). The soil moisture drought index (SMDI; Hollinger et al., 1993) and crop-specific drought index (CSDI; Meyer and Hubbard, 1995) appeared after CMI. Furthermore, CSDI is divided into a corn drought index (CDI; Meyer and Pulliam, 1992) and soybean drought index (SDI; Meyer and Hubbard, 1995), and vegetation condition index (VCI; Liu and Kogan, 1996). Besides these indices, indices of Penman (1948), Thornthwaite (1948, 1963), and Keetch and Byram (1968) have been used in limited cases (Hayes, 1996). Heim (2002) gave a comprehensive review of 20th century drought indices used in the United States.

Based on the studies for drought indices, practically all drought indices use precipitation either singly or in combination with other meteorological elements, depending upon the type of requirements, which were also suggested by WMO (1975). For example, a combination of hydrometeorlogical variables includes: temperature and precipitation (Marcovitch's index, 1930; Palmers index, 1965; Crop moisture index, 1968), precipitation and soil moisture (moisture adequacy index, 1957; Keetch-Bryam drought index, 1968) and only precipitation (SPI, 1993).

The following section discusses commonly used drought indices, their usefulness, limitations, and comparison between different indices.

5.1. Standardized precipitation index

The standardized precipitation index (SPI) for any location is calculated, 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 to a normal distribution so that the mean SPI for the location and desired period is zero (McKee et al., 1993; Edwards and McKee, 1997). The fundamental strength of SPI is that it can be calculated for a variety of time scales. This versatility allows SPI to monitor short-term water supplies, such as soil moisture which is important for agricultural production, and long-term water resources, such as groundwater supplies, streamflow, and lake and reservoir levels. Soil moisture conditions respond to precipitation anomalies on a relatively short scale. Groundwater, streamflow, and reservoir storage reflect the long-term precipitation anomalies. For example, Szalai et al. (2000) examined how strong the connection of SPI is with hydrological features, such as streamflow and groundwater level at stations in Hungary. Correlation of SPI with streamflow was the highest on a 2-month timescale, while for groundwater levels the best correlations were found at widely different time scales. They also concluded that agricultural drought (proxied by soil moisture content) was replicated best by SPI on a scale of 2–3 months. SPI has been used for studying different aspects of droughts, for example, forecasting (Mishra and Desai, 2005a; Mishra et al. 2007), frequency analysis (Mishra et al. 2009), spatio temporal analysis (Mishra and Desai, 2005b; Mishra and Singh, 2009) and climate impact studies (Mishra and Singh, 2009).

5.1.1. Limitations of SPI

The length of precipitation record and nature of probability distribution play an important role for calculating SPI and the following section discusses limitations of SPI.

5.1.2. Length of precipitation record

The length of a precipitation record has a significant impact on the SPI values. Similar and consistent results are observed when the SPI values, computed from different lengths of record, have similar gamma distributions over different time periods. However, the SPI values are significantly discrepant when the distributions are different. It is recommended that the SPI user should be aware of the numerical differences in the SPI values if different lengths of record are used in interpreting and making decisions based on the SPI values. For example, Wu et al. (2005) investigated the effect of the length of record on the SPI calculation by examining correlation coefficients, the index of agreement, and the consistency of dry/wet event categories between the SPI values derived from different precipitation record lengths. The reason for discrepancy in the SPI value is due to changes in the shape and scale parameters of the gamma distribution when different lengths of record are involved.

5.1.3. Probability distributions

The use of different probability distributions affect the SPI values as the SPI is based on the fitting of a distribution to precipitation series. Some of the commonly applied distributions include: gamma distribution (McKee et al., 1993; Edwards and McKee, 1997; Mishra and Singh, 2009); and Pearson Type III distribution (Guttman, 1999); and lognormal, extreme value, and exponential distributions have been widely applied to simulations of precipitation distributions (Lloyd-Hughes and Saunders, 2002; Madsen et al., 1998; Todorovic and Woolhiser, 1976; Wu et al., 2007). Two types of problems arise: (i) When SPIs are calculated for long time scales (longer than 24 months) fitting a distribution might be biased due to the limitation in data length and it is true that when finer resolutions of spatial analysis need to be investigated, long data sets are not available in many catchments around the world. Lloyd-Hughes and Saunders (2002) and Sonmez et al. (2005) reported biased SPI values. (ii) For dry climates where precipitation is seasonal in nature and zero values are common, there will be too many zero precipitation values in a particular season. In these climatic zones, the calculated SPI values at short time scales may not be normally distributed because of the highly skewed underlying precipitation distribution and because of the limitation of the fitted gamma distribution. This may be prone to large errors while simulating precipitation distributions in dry climates from small data samples.

5.2. Palmer drought severity index (PDSI)

Using precipitation and temperature for estimating moisture supply and demand within a two-layer soil model, Palmer (1965) formulated what is now referred to as the Palmer drought index (PDI). This was the first comprehensive effort to assess the total moisture status of a region. Since its inception, some modified versions of PDSI have evolved. For example, Karl (1986) described a modified version known as the Palmer hydrological drought index (PHDI) which is used for water supply monitoring. For operational purposes, a real time version of PDSI, called modified PDSI (PDI), was introduced by Heddinghaus and Sahol (1991).

PDSI is perhaps the most widely used regional drought index for monitoring droughts. The index has been used to illustrate the areal extent and severity of various drought episodes (Palmer, 1967; Karl and Quayle, 1981) and to investigate the spatial and temporal drought characteristics (Lawson et al., 1971; Klugman, 1978; Karl and Koscielny, 1982; Diaz, 1983; Soule, 1993; Jones et al., 1996) as well as to explore the periodic behavior of droughts (Rao and Padmanabhan, 1984), monitoring hydrologic trends, crop forecasts, and assessing potential fire severity (Heddinghaus and Sahol, 1991), droughts over large geographic areas (Johnson and Kohne, 1993), and drought forecasting (Kim and Valdes, 2003; Özger et al., 2009).

5.2.1. Limitations of PDSI

Some of the rules used to establish PDSI are arbitrary and the limitations of PDSI have been documented in several studies (Alley, 1984; Karl and Knight, 1985; Willeke et al., 1994; McKee et al., 1995; Guttman, 1997). Limitations of PDSI include: (1) an inherent time scale making PDSI more suitable for agricultural impacts and not so much for hydrologic droughts, (2) assumptions that all precipitation is rain, thus making values during winter months and at high elevations often questionable. PDSI also assumes that runoff only occurs after all soil layers have become saturated, leading to an underestimation of runoff, and (3) PDSI can be slow to respond to developing and diminishing droughts (Hayes et al., 1999). While there are criticisms of PDSI, there are positive aspects as well. It has been in use for a long time, and has been well tested and verified in many cases. It accounts for temperature and soil characteristics, and is standardized so comparisons of different climatic zones are possible. PDSI is also sensitive to precipitation and temperature which is discussed in the following section.

5.2.2. Sensitivity of PDSI to temperature and precipitation

PDSI is sensitive to both temperature and precipitation. Numerical experiments have been used to evaluate the influence of temperature and precipitation anomalies on PDSI and its related indices, e.g., Palmer hydrological drought index (PHDI) (Guttman, 1991). It has been observed that: (i) precipitation anomalies tend to dominate the change of PDSI in cold season when evaporation is minimal; (ii) the effect of temperature on PDSI becomes more important in warm seasons, however the response of PDSI often lags anomalies of temperature and precipitation by a few months (e.g., Karl, 1986), this lag relationship is not well understood; (iii) because of the dependence of PDSI on climatologically appropriate rainfall, which is a function of time and varies with surface air temperature, PDSI can be equally affected by temperature and precipitation, when both have similar magnitudes of anomalies. The effect of temperature on PDSI complicates the usage of the index in interpreting precipitation anomalies and its application in inferring precipitation variations, particularly from reconstructed PDSI (Hu and Willson, 2000).

5.3. Crop moisture index

Palmer (1968) developed crop moisture index (CMI) to evaluate short-term moisture conditions (week to week) across major crop-producing regions. Computation of CMI involves the use of weekly values of temperature and precipitation to compute a simple moisture budget. Variables from the moisture budget computation are compared to long-term average values and are modified by empirical relations to arrive at final CMI values.

5.3.1. Limitations of CMI

Based on sensitive analysis an increase in CMI may occur with an increase in potential evapotranspiration. An increase in the CMI value indicates wetter moisture conditions and there is no case in nature where an increase in potential evaporation would produce wetter moisture conditions and such a case was reported by Juhasz and Kornfield (1978). The unnatural response of CMI to changes in temperature is due to the dependence of the abnormal evapotranspiration term on the magnitude of potential evapotranspiration. Secondly, CMI is not a good long-term drought monitoring tool. CMI's rapid response to changing short-term conditions may provide misleading information about long-term conditions. However, CMI is most effective for measuring agricultural droughts during warm seasons (i.e., growing season) (Heim, 2002).

5.4. Surface water supply index

The surface water supply index (SWSI) (Shafer and Dezman, 1982) was primarily developed as a hydrological drought index and it is calculated based on monthly non-exceedance probability from available historical records of reservoir storage, streamflow, snow pack, and precipitation. The purpose of SWSI is primarily to monitor abnormalities in surface water supply sources. Hence, it is a good measure to monitor the impact of hydrologic droughts on urban and industrial water supplies, irrigation and hydroelectric power generation. Four inputs are required within SWSI: snowpack, streamflow, precipitation, and reservoir storage (Wilhite and Glantz, 1985; Doesken et al., 1991; Garen, 1993). Because it is dependent on the season, SWSI is computed with only snowpack, precipitation, and reservoir storage in winter. During summer months, streamflow replaces snowpack as a component within the SWSI equation.

5.4.1. Limitations of SWSI

The definition of surface water supply and the factor weights vary with spatial scale (one watershed to another) as well as temporal scale (season or month) due to differences in hydroclimatic variability resulting in SWSIs with differing statistical properties. For example, the hydroclimatic differences that characterize river basins in the Western United States result in SWSIs that do not have the same meaning and significance in all areas and at all times (Heim, 2002; Doesken et al., 1991).

5.5. Vegetation condition index

Since the 1970s, several studies have used satellite land observation data to monitor a variety of dynamic land surface processes (e.g., Anderson et al., 1976; Reed et al.,1994; Yang et al., 1998; Peters et al., 2002; Gu et al., 2007). Satellite remote sensing provides a synoptic view of the land and a spatial context for measuring drought impacts which have proved to be a valuable source of timely, spatially continuous data with improved information on monitoring vegetation dynamics over large areas. The vegetation condition index (VCI), computed from satellite advanced very high resolution radiometer (AVHRR) radiance (visible and near infrared) data adjusted for land, climate, ecology, and weather conditions, shows promise when used for drought detection and tracking (Kogan, 1995). The VCI allows detection of drought and measurement of the time of its onset and its intensity, duration, and impact on vegetation. However, since the VCI is based on vegetation, it is primarily useful for the summer growing season. It has limited utility for cold seasons when vegetation is largely dormant (Heim, 2002).

5.6. Recent developments in drought indices

The following section discusses drought indices which have been developed recently.

5.6.1. Effective precipitation (EP)

It is the summed value of daily precipitation with a time-dependent reduction function which can more precisely determine drought duration, monitor an ongoing drought, and define the variety of ways in which drought characteristics can be described (Byun and Wilhite, 1999). Three additional indices complement EP. The first index is each day's mean of EP (MEP). This index shows climatological characteristics of precipitation as a water resource for a station or area. The second index is the deviation of EP (DEP) from MEP. The third index is the standardized value of DEP (SEP). Using these three indices, consecutive days of negative SEP, which can show the onset, the end date, and the duration of a water deficit period, are categorized.

5.6.2. Based on soil moisture

Narasimhan and Srinivasan (2005) developed soil moisture deficit index (SMDI) and evapotranspiration deficit index (ETDI) based on weekly soil moisture and evapotranspiration simulated by a calibrated hydrologic model, respectively. The drought indices were derived from soil moisture deficit and evapotranspiration deficit and scaled between −4 and +4 for spatial comparison of droughts, irrespective of climatic conditions. Recently soil moisture index (SMI; Hunt et al., 2009) was developed based on the actual water content and known field capacity and wilting point.

5.6.3. Standardized runoff index (SRI)

This index is based on the concept of standardized precipitation index (SPI), discussed earlier. Shukla and Wood (2008) derived standardized runoff index (SRI) which incorporates hydrologic processes that determine the seasonal loss in streamflow due to the influence of climate. As a result, on month to seasonal time scales SRI is a useful complement to SPI for depicting hydrological aspects of droughts.

5.6.4. Based on remote sensing

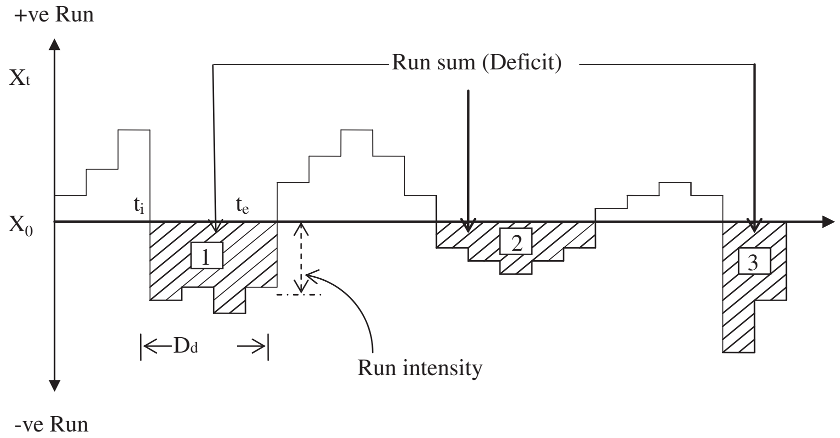
The normalized difference water index (NDWI) is a more recent satellite-derived index from the NIR and short wave infrared (SWIR) channels that reflect changes in both the water content and spongy mesophyll in vegetation canopies. NDWI calculated from the 500-m SWIR band of MODIS has recently been used to detect and monitor the moisture condition of vegetation canopies over large areas (Xiao et al., 2002; Jackson et al., 2004; Maki et al., 2004; Chen et al., 2005; Delbart et al., 2005). Because NDWI is influenced by both desiccation and wilting of vegetative canopy, it may be a more sensitive indicator than normalized difference vegetation index (NDVI) for drought monitoring.

5.6.5. Drought monitor (DM)

NOAA, USDA and national drought mitigation derived a weekly drought monitor (DM) product that incorporates climatic data and professional input from all levels (Svoboda, 2000). The key parameters are objectively scaled to five DM drought categories. The classification scheme includes categories D0 (abnormally dry area) to D4 (exceptional drought event, likened to a drought of record) and labels indicating the sectors being impacted by droughts (A for agricultural impacts, W for hydrological impacts, and F to indicate the high risk of wildfires). A limitation of DM lies in its attempt to show droughts at several temporal scales (from short term drought to long-term drought) on one map product (Heim, 2002).

5.7. Comparison of drought indices

Several attempts have been made to compare indices to find the most suitable indices for specific objectives of drought monitoring. There has been a lot of comparison between SPI and PDSI for monitoring droughts. Some of the differences include: (i) special characteristics of PDI vary from site to site (example: USA case study by Guttman (1999)) while those of SPI do not vary from site to site. Also, PDI has a complex structure with an exceptionally long memory, while SPI is an easily interpreted, simple moving average process. Therefore, SPI can be used as the primary drought index, because it is simple, spatially invariant in its interpretation, and probabilistic, so it can be used in risk and decision analysis (Guttman, 1998). (ii) SPI is more representative of short-term precipitation than PDSI and thus is a better indicator for soil moisture variation and soil wetness (Sims et al., 2002). (iii) SPI is a better predictor of crop production, as it represents the moisture state of soil better (Quiring and Papakyriakou, 2003). (iv) SPI provides a better spatial standardization than does PDSI with respect to extreme drought events (Lloyd-Hughes and Saunders, 2002). (v) Based on 14 well-known drought indices using a weighted set of six evaluation criteria, Keyantash and Dracup (2002) found that



1. Drought with the highest severity;
2. Drought with the longest duration;
3. Drought with the highest intensity

Fig. 1. Drought characteristics using the run theory for a given threshold level.

SPI was a valuable estimator of drought severity. (vi) SPI detects the onset of a drought earlier than PDSI (a case study: Texas, by Hayes et al. (1999)).

Based on seven drought indices, Morid et al. (2006) compared the performances in the Tehran province of Iran. The indices included 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). The results showed that SPI, CZI and *Z*-Score performed similarly with regard to drought identification and responded slowly to drought onset. DI appears to be very responsive to rainfall events of a particular year, but it has inconsistent spatial and temporal variation. SPI and EDI have been found to be able to detect the onset of a drought, its spatial and temporal variation consistently and EDI has been found to be more responsive to the emerging drought and perform better.

It can be inferred from the above discussion that the performance of drought indices is region specific. This is due to the variability in meteorological variables as well as streamflow characteristics which are generally used for deriving indices. The following section discusses the approach for calculating drought parameters using drought indices.

5.8. Drought identification

This section discusses the method commonly used for identification of drought properties based on drought indices discussed in the previous section. Yevjevich (1967) proposed the theory for identifying drought parameters and investigating their statistical properties: (a) duration, (b) severity, and (c) intensity. The most basic element for deriving these parameters is the truncation or threshold level, which may be a constant or a function of time. A run is defined as a portion of time series of drought variable $X_{t,}$ in which all values are either below or above the selected truncation level of X_0; accordingly it is called either a negative run or a positive run. Fig. 1 represents a plot of a drought variable denoted by X_t, which is intersected at many places by the truncation level $X_{0,}$ which can be a deterministic variable, a stochastic variable, or a combination thereof. Various statistical parameters concerning drought duration, magnitude and intensity at different truncation levels are much useful for drought characterization.

A drought event has the following major components (Dracup et al., 1980) as derived from Fig. 1 which include: (a) Drought initiation time (t_i): it is the starting of the water shortage period, which indicates the beginning of a drought. (b) Drought termination time (t_e): it is the time when the water shortage becomes sufficiently small so that drought conditions no longer persist. (c) Drought duration (D_d): it is expressed in years/months/weeks, etc., during which a drought parameter is continuously below the critical level. In other words, it is the time period between the initiation and termination of a drought. (d) Drought severity (S_d): it indicates a cumulative deficiency of a drought parameter below the critical level. (e) Drought intensity (I_d): it is the average value of a drought parameter below the critical level. It is measured as the drought severity divided by the duration. The run theory has been applied in several drought models and analyzes (for example, Sen 1976, 1980; Dracup et al., 1980; Loaiciga and Leipnik, 1996; Mishra et al., 2007).

6. Use of paleoclimatology in drought studies

Paleoclimatology is the study of climate considered on the scale of the entire history of earth. It uses records from ice sheets, tree rings, sediments, and rocks to determine the past state of the climate system on earth. Paleoclimatic data offer a way to evaluate the severity, duration, and extent of twentieth-century droughts in the context of the past two millennia (e.g., Overpeck, 1996). The following section discusses different techniques of the use of paleoclimatic data for understanding the historical drought of a region.

6.1. Tree ring reconstruction for drought studies

Paleoclimatology studies, and especially dendroclimatology (it is the science of determining past climates from tree rings), form a valuable source of information for analyzing drought recurrences. Tree rings probably offer the best means of reconstructing large scale and highly resolved patterns of climate (Fritts, 1991; Cook and Kairiukstis, 1990). For example, Woodhouse and Overpeck (1998) reviewed a wide range of the paleoclimatic literature, including a variety of data sources like tree-ring data and instrumental records, and suggested that droughts more severe than those of the 1930s and 1950s, which had the most severe impact on the continental United States, were likely to occur in the future. Also, there is evidence for multidecadal droughts during the late thirteenth and sixteenth centuries that were of much greater severity and duration than those of the twentieth century (Woodhouse and Overpeck, 1998). Another example includes: Gedalof et al. (2004) used a network of 32 drought sensitive tree-ring chronologies to reconstruct mean water year flow on the Columbia River at Dalles, Oregon, since 1750. Their findings suggest that the relationship between drought and streamflow has changed over time.

Tree-ring data have been employed to formulate yearly time series relationships with drought indices, PDSI, PHDI, and ZNDX. As an example, Cook et al. (1999) described the development of summer drought reconstructions using PDSI for the continental United States at a 2° latitude ×3° longitude grid estimated from a dense network of annual tree-ring chronologies. In China Li et al. (2007) presented drought reconstruction for Northcentral China based on PDSI.

Recently, well verified tree-ring based reconstructions have been undertaken in USA, for example, for the Sacramento River basin (Meko et al., 2001), the Gila River (Meko and Graybill, 1995), Crater Lake (Peterson et al., 1999), the Colorado River (Hidalgo et al., 2001).

6.2. Use of peat land for centuary old drought studies

Peat lands are also used for historical drought analysis at certain places. Paleohydrological records from lake sediments in the northern Great Plains have been employed to extend high-resolution records of the late Holocene drought variability into the mid-continent (Laird et al., 2003). Proxy-climate records from peatlands in the region show substantial decadal to millennial scale hydroclimatic variability during the late Holocene, indicating the region, despite being relatively humid, is susceptible to large, ecologically significant droughts (Schoning et al. 2005).

Since 2002, the Climate Monitoring Branch of NOAA's National Climatic Data Center has begun collaborating with its Palaeoclimatology Section to incorporate pre-instrumental perspectives into monthly and annual state of the climate (SoC) reports (Eakin et al., 2003). These palaeoclimatic data provide a multi-century baseline from which the user can better gauge recent hydroclimatic episodes relative to those of the previous centuries. As longer and longer records become available, new methods need to be developed to quantify uncertainties in the climate system and to extract information on climatic variability that will be relevant to researchers, policy makers, and land managers (Biondi et al., 2005).

7. Relationship between drought and large scale climate indices

The concept that distant regions are affected by large scale changes in atmospheric circulation patterns is defined as atmospheric teleconnections. Many indices have been developed to measure the variability of oceanic and atmospheric parameters. These indices include the southern oscillation index (SOI), the multivariate ENSO index (MEI; Wolter and Timlin, 1993), the Pacific–North American (PNA) index (Overland et al., 2002), the Pacific Decadal Oscillation (PDO; Bond and Harrison, 2000; Mantua et al., 1997), and the North Atlantic Oscillation (NAO; Hurrell, 1995). It has been documented that climatic variability influences regional hydrologic activity (Redmond and Koch, 1991; Kahya and Dracup, 1993), but casualty is not well understood. Thus, this section intends to show the impact of variability in global oceanic and atmospheric indices on regional droughts and drought parameters.

Several studies have been carried out for understanding droughts and establishing their relation to large scale climate indices. For example, Hoerling and Kumar (2003) analyzed the 1998–2002 droughts, which affected the United States, Southern Europe, and Southwest Asia, and they found that this prolonged and widespread drought was linked to a common oceanic influence. Piechota and Dracup (1996) used monthly PDSI time series to investigate the hydroclimatic response in the United States to the extreme phases of Southern Oscillation (El Nino and La Nina). Their study observed the strongest relationship existing between El Nino and extreme drought years in the Pacific Northwest. A strong relationship was also observed in the Southern United States, where dry conditions occurred consistently during La Nina events. In a recent study using wavelet transforms and cross-correlations and Kriging, Özger et al. (2009) investigated the spatial structure of teleconnections of both El Niño Southern oscillation (ENSO) and Pacific Decadal Oscillation (PDO) to droughts during the 20th century for the state of Texas. Each region in Texas had different responses but arid regions showed stronger correlations to climate anomalies than did sub-tropic humid regions.

Shabbar and Skinner (2004) examined the Canadian summer (June–August) Palmer drought severity index (PDSI) variations and winter (December–February) global sea surface temperature (SST) variations for a 63-year period of 1940–2002. Extreme wet and dry Canadian summers were related to anomalies in the global SST pattern in the preceding winter season.

Chang (1997) investigated the ENSO extreme climate events and their impacts on Asian deltas. The recent Central and Southwest Asian drought, for example, was attributed to an enhanced signal in the warm pool region associated with ENSO (Barlow et al., 2002). A severe drought over three years (1998–2001), which affected over 60 million people in central and southwest (CSW) Asia related to a combination of the prolonged duration of La Niña and unusually warm SSTs in the West Pacific, which may have enhanced the regional dynamics of the warm pool. Given the demise of La Niña in early 2001, conditions may be favorable for a return toward normal in CSW Asia (Barlow et al., 2002).

Bordi and Sutera (2001) found dry conditions over Europe, Eastern Asia, central Africa and the Caribbean region to be interconnected and affected by the tropical climatic variability. Similarly, Chiew et al. (1998) showed that the occurrence of droughts in Australia was closely associated with the El Niño events and Quinn (1992) analyzed Southern oscillation related climatic activity using the Nile River flood data.

7.1. Examples of decadal/interannual droughts linked to climate indices

Droughts on the decadal time scale (i.e., such as the 1930s drought in the United States or the recent North American drought that occurred over a roughly 5–10 year time period) have had severe impacts and have also been linked to the SST anomalies in the tropical Pacific (Schubert et al., 2004; Hoerling and Kumar, 2003). Rajagopalan et al. (2000) investigated the spatial structure of teleconnections between both the winter ENSO and global sea surface temperatures (SSTs), and a measure of continental US summer drought during the twentieth century.

Similar decadal time scale droughts in the South Asian monsoon region have been connected to low-frequency SST variations in the tropical Pacific (Barlow et al., 2002; Krishnan and Sugi, 2003). Droughts associated with Indian monsoon failure, also occurring on the interannual time scale, are similarly well-documented characteristics of climate in the South Asian region and are associated with SST anomalies in the tropical Pacific Ocean and Indian Ocean (Meehl and Arblaster, 2002).

Richard et al. (2001) studied rainfall variability and changes in the interannual variability amplitude of the 20th century droughts in Southern Africa based on the analysis of oceanic and atmospheric conditions linked to these changes. There are no significant changes in the January–March rainfall totals during the last century. However, summer rainfall shows a change in the intensity of interannual variability. SST and atmospheric parameter composites show that droughts before and after 1970 are not associated with the same anomaly patterns. The 1950–1969 droughts are linked to regional oceanic and atmospheric anomalies, whereas the 1970–1988 droughts are associated with global tropical oceanic and atmospheric conditions mainly linked to ENSO.

7.2. Relation between agricultural drought and large scale climate indices

Depending on the agricultural production of a catchment, agricultural droughts can be investigated and some of the research carried out in the last decade links crop production with climate indices. Links between ENSO and crop yields have been shown for the United States (Handler, 1990; Phillips et al., 1996), for Australia (Nicholls, 1985; Meinke et al., 1996), for Mexico (Dilley, 1997), Northeastern Brazil (Rao et al., 1997), and Southern Africa (Cane et al., 1994; Phillips and McGregor, 1998). Keplinger and Mjelde (1994) found a correlation between sorghum yields and SO in Argentina, Australia, India, and Texas. Nicholls (1985) suggested a close relationship between SO and Australian crop yield. Significant correlations between forecasted sea surface temperature and the maize yields in Zimbabwe as reported by Cane et al. (1994). Hammer et al. (1996) showed that the knowledge of SO index allowed Australian wheat producers to manage risk and increase gross margins for wheat production. Peru has incorporated SO forecasts into their national planning process (Lagos and Buzier, 1992). Mjelde and Keplinger (1998) used time series models to examine the impact of southern oscillation (SO) extreme events in estimating and forecasting sorghum and winter wheat yields in Texas. It is well understood that droughts around the globe are related to large scale climate indices. Understanding these linkages will be useful for predicting different types of droughts, including agricultural droughts based on crop yield. The following section draws conclusion based on the above discussion on different aspects of droughts.

8. Conclusions

As a complex natural hazard drought is best characterized by multiple climatological and hydrological parameters. Improving our understanding of the relationships between these parameters is necessary to develop measures to reduce the impacts of droughts. Therefore, an understanding of the association of droughts with climatic, oceanic, and local factors like water demand and environmental parameters is essential in order to combat the effects of a drought in a proactive manner by addressing vulnerabilities through a risk management approach. It is observed that most continents around the globe have experienced frequent droughts in the last three decades and this condition is being aggravated due to growing water demands with limited source of water as well as spatio-temporal changes in climatic patterns. Looking at impacts due to frequent drought episodes it will be necessary for all water resources planners to look at impacts of droughts based on historical, present and future scenarios likely to occur. Based on this review the following conclusions can be drawn:

1. In view of four types of droughts which include meteorological, hydrological, agricultural and socio-economic droughts, it will be appropriate to introduce groundwater drought as another important type of drought. Understanding a groundwater drought will remain a challenge for water resources planners. This is because of large exploitation of groundwater due to limited surface water as well as understanding complicated hydrogeological processes with respect to the change in the dynamics of hydro-meteorological variables with changes in land cover.
2. There is a continuous effort going onto derive efficient drought indices with the hope of better monitoring drought conditions which can be useful for early warning as well as to derive better drought parameters. It is observed that drought indices can only reflect drought conditions based on hydro-meteorological variables but it is unable to quantify the economic losses. There is room to improve drought indices further to get better information. Drought indices can be explored further, considering needs of the user in the region and classifying droughts based on their severity. For example, with a similar amount of annual precipitation in two regions one with lower population and the other higher population, it is obvious that a region with higher population will be more susceptible to drought. However, when the drought conditions are defined based on precipitation then the derived drought indices will reflect similar droughts in both regions, however it is not so in actual conditions. Therefore, the water demand of the region needs to be incorporated in drought indices.
3. Deriving drought indices for any region needs to be done cautiously. For example, the commonly used index SPI is a precipitation defined product and the problem arises when precipitation contains a number of significant zero values (mostly in dry climates). This will be a problem due to limitations of the gamma distribution (commonly fitted in most cases) as well as due to a highly left skewed distribution. Due to limitations of data, simulating precipitation using a probability distribution might cause errors while deriving drought indices if the probability distribution is not chosen properly. Similarly, drought indices derived from soil moisture lacks quality data due to high heterogeneity involved at different scale measurements which has been a challenging task. Also precipitation changes over time, so it is important to check the probability distribution parameters over different time scales to make sure it does not affect drought indices in a significant way. A similar assumption will also hold for soil moisture, as it largely depends on precipitation.
4. For categorizing drought severity it is important to define a threshold level. Currently most of the studies focus on a constant threshold level (for example, long term mean of the drought variable). However, in practice the water demand in a region is dominated by seasonal characteristics. For better understanding of drought parameters (i.e., severity, duration and intensity), the selection of a threshold will be crucial and more research is needed for choosing the threshold level for different hydroclimatic regions.
5. It is important to analyze historical droughts before planning any new projects as well as reviewing existing water resources projects. This analysis will help generate information related to water deficits with respect to water demands during drought periods. This information will be useful for developing water resources structures to meet the challenges likely to occur in case there is a drought like situation in future. This study is possible, looking at the long term hydrometeorlogical data which are rarely available for more than 100 years. In order to overcome the problem of data shortage, paleoclimatic data can be explored for extending hydrometeorlogical time series to have an idea about historical droughts. These studies are needed in regions critically affected by increasing drought patterns to understand whether the drought is periodic in nature or is due to the impact of climate change or is human-made due to growing water demand. This type of study exploring different combinations has not been reported so far.
6. It is understood that drought incidences around the globe are related to large scale climate indices. Most of the studies have been focused on the national or regional scale. However, understanding at the local scale has still been a critical issue due to the heterogeneity in spatio-temporal hydro-meteorological variability. For example, studies carried out for understanding teleconnections between hydrological droughts with climatic indices can be improved using virgin streamflows instead of abstracted flows which are becoming heterogeneous in coarse of time. Understanding the relationship between climate indices and virgin streamflow for drought studies are useful in getting actual information about changing climatic patterns, as abstracted streamflow is influenced by several factors which are highly dominated by human interventions.

Although the paper has examined a number of literature sources, it seems to be virtually impossible to include in a review all publications. It is possible that some aspects of the subject have either been overlooked or only briefly referred to. Some of the aspects of drought research have been deliberately considered only marginally here and they deserve a more comprehensive, special review. It is expected that these gaps could be filled by subsequent contributions and that there is scope for further discussion about the drought research possibly in the broader context of future development of the entire hydrological science and natural hazards.

Acknowledgments

The authors are grateful to Dr. Geoff Syme (Editor), Associate Editor and anonymous reviewers for their useful comments and suggestions. This work was financially supported by the United States Geological Survey (USGS, Project ID: 2009TX334G) and TWRI through the project ‘Hydrological Drought Characterization for Texas under Climate Change, with Implications for Water Resources Planning and Management.

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