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Drought Monitoring and Assessment: Status and Trends in the United States

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Abstract
Drought is a normal, recurring feature of climate. The characteristics of this hazard, along with its far-reaching impacts, make its effects on society, economy, and environment difficult to identify and quantify. A national drought watch system has been recommended as a necessary component of drought assessment and management. The National Drought Mitigation Center, in collaboration with others, has undertaken a number of drought watch activities for the past few years, using a variety of resources available over the Internet. These resources include tools such as the Standardized Precipitation Index, a new drought index that is more reliable for detecting emerging drought conditions.

1. Introduction

The economic, social, and environmental costs and losses associated with drought in the United States are significant. In 1995, the U.S. Federal Emergency Management Agency (FEMA) estimated annual losses attributable to drought at US $6–8 billion. A critical component of planning for drought is the provision of timely and reliable seasonal forecasts and informational products that help decision makers at all levels reduce the impacts of drought events. A comprehensive, integrated national climate monitoring or drought watch system has been recommended for some time (Wilhite et al., 1986; Riebsame et al., 1991; Wilhite and Wood, 1994), but no action on these recommendations has taken place. The Internet and the wide range of data and information that is readily accessible to users have made the development of an integrated climate monitoring system a more executable task.

The purpose of this paper is to document the current status of drought monitoring and assessment in the United States. This paper begins with a brief overview of some of the concepts of drought and how it differs from other natural hazards. Understanding the unique characteristics of drought is crucial to establishing an effective and comprehensive monitoring and early warning system. The paper will then discuss more specifically the drought watch activities of the National Drought Mitigation Center (NDMC) and its collaborative activities with the Monitoring, Assessment, and Prediction (MAP) Working Group of the Western Drought Coordination Council (WDCC). The WDCC was formed in 1997 in response to the severe drought that affected many western states in 1996. The WDCC was developed as a result of a Memorandum of Understanding between the Western Governors' Association and key federal agencies. The value of the newly developed Standardized Precipitation Index (SPI) in monitoring the onset, development, and severity of drought conditions will also be included in this discussion.

2. Drought: The Concept

Drought is a normal, recurring feature of climate; it occurs in virtually all climatic regimes. It occurs in high as well as low rainfall areas. It is a temporary aberration, in contrast to aridity, which is a permanent feature of the climate and is restricted to low rainfall areas. Drought is the consequence of a natural reduction in the amount of precipitation received over an extended period of time, usually a season or more in length, although other climatic factors (such as high temperatures, high winds, and low relative humidity) are often associated with it in many regions of the world and can significantly aggravate the severity of the event. Drought is also related to the timing (i.e., principal season of occurrence, delays in the start of the rainy season, occurrence of rains in relation to principal crop growth stages) and the effectiveness (i.e., rainfall intensity, number of rainfall events) of the rains. Thus, each drought year is unique in its climatic characteristics and impacts.

Drought differs from other natural hazards in several ways. First, since the effects of drought often accumulate slowly over a considerable period of time and may linger for years after the termination of the event, the onset and end of drought is difficult to determine. Because of this, drought is often referred to as a creeping phenomenon (Tannehill, 1947). Although Tannehill made this statement more than fifty years ago, climatologists continue to struggle with recognizing the onset of drought and scientists and policy makers continue to debate the basis (i.e., criteria) for declaring an end to a drought.

Second, the absence of a precise and universally accepted definition of drought adds to the confusion about whether or not a drought exists and, if it does, its degree of severity. Realistically, definitions of drought must be region and application (or impact) specific. This is one explanation for the scores of definitions that have been developed. Wilhite and Glantz (1985) analyzed more than 150 definitions in their classification study, and many more exist. Although the definitions are numerous, many do not adequately define drought in meaningful terms for scientists and policy makers. The thresholds for declaring drought are arbitrary in most cases (i.e., they are not linked to specific impacts in key economic sectors). These types of problems are the result of a misunderstanding of the concept by those formulating definitions and the lack of consideration given to how other scientists or disciplines will eventually need to apply the definition in actual drought situations (e.g., assessments of impact in multiple economic sectors, drought declarations or revocations for eligibility to relief programs).

Third, drought impacts are nonstructural in contrast to floods, hurricanes, and most other natural hazards. Its impacts are spread over a larger geographical area than are damages that result from other natural hazards. For these reasons, the quantification of impacts and the provision of disaster relief are far more difficult tasks for drought than they are for other natural hazards. Emergency managers, for example, are more accustomed to dealing with impacts that are structural and localized, responding to these events by restoring communication and transportation channels, providing emergency medical supplies, ensuring safe drinking water, and so forth.

These characteristics of drought have hindered the development of accurate, reliable, and timely estimates of severity and impacts and, ultimately, the formulation of drought contingency plans by most governments. Drought severity is dependent not only on the duration, intensity, and spatial extent of a specific drought episode but also on the demands made by human activities and vegetation on a region's water supplies. The characteristics of drought, along with its far-reaching impacts, make its effects on society, economy, and environment difficult to identify and quantify. This continues to be a formidable challenge to those scientists involved in operational climate assessments.

Many people consider drought to be largely a natural event. In reality, the risk associated with drought for any region is a product of both the region's exposure to the event (i.e., probability of occurrence at various severity levels) and the vulnerability of society to the event. The natural event (i.e., meteorological drought) is a result of the occurrence of persistent large-scale disruptions or anomalies in the global circulation pattern of the atmosphere. Exposure to drought varies spatially and there is little, if anything, that we can do to alter drought occurrence. Vulnerability, on the other hand, is determined by social factors such as population, demographic characteristics, technology, policy, and social behavior. These factors change over time, and thus vulnerability is likely to increase or decrease in response to these changes. Subsequent droughts in the same region will have different effects, even if they are identical in intensity, duration, and spatial characteristics, because societal characteristics will have changed. However, much can be done to lessen societal vulnerability to drought.

3. Drought Characteristics and Severity

Droughts differ from one another in three essential characteristics: intensity, duration, and spatial coverage. Intensity refers to the degree of the precipitation shortfall and/or the severity of impacts associated with the shortfall. It is generally measured by the departure of some climatic index from normal and is closely linked to duration in the determination of impact. Many indices of drought are in widespread use today, such as the decile approach (Gibbs and Maher, 1967; Lee 1979; Coughlan, 1987) used in Australia, the Palmer Drought Severity Index and Crop Moisture Index (Palmer, 1965 and 1968; Alley, 1984) in the United States, and the Yield Moisture Index (Jose et al., 1991) in the Philippines and elsewhere. A relatively new index that is gaining popularity in the United States and worldwide is the Standardized Precipitation Index (SPI), developed by McKee et al. (1993 and 1995). The SPI will be discussed in greater detail in later sections of this paper.

Another distinguishing feature of drought is its duration. Droughts usually require a minimum of two to three months to become established but then can continue for months or years. The magnitude of drought impacts is closely related to the timing of the onset of the precipitation shortage, its intensity, and the duration of the event.

Droughts also differ in terms of their spatial characteristics. The areas affected by severe drought evolve gradually, and regions of maximum intensity shift from season to season. During the drought of 1934 in the United States, the area affected was approximately 65% of the country (see fig. 1). By contrast, drought affected more than 95% of the Great Plains region in 1934. In the United States, it is unusual for drought not to exist in a portion of the country each year. Figure 1 illustrates that in the United States, the percent area affected by drought is commonly greater than 10%. A recent analysis of drought occurrence by the U.S. National Drought Mitigation Center (NDMC) for the 48 contiguous states in the United States demonstrated that severe and extreme drought affected more than 25% of the country in one out of four years.

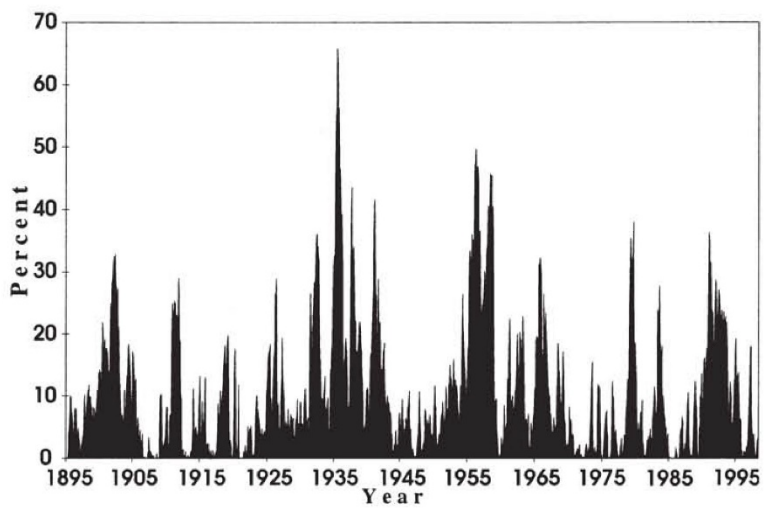

Figure 1. Percentage area of United States in severe and extreme drought, 1895–1995.

4. Integrated Climate Monitoring/National Drought Watch System

The need for a national drought watch system has been acknowledged for some time in the literature as part of a more comprehensive approach to drought assessment and management. Following the creation of the NDMC, one of our first goals was to create a "one-stop shopping" section of our website that would provide users with access to all of the information necessary to develop a timely and reliable climatic assessment for their state or region. The development of the "drought watch" section was undertaken because no routine national or regional assessment was available from federal agencies. However, all of the components necessary to assess current climate conditions and the long-range outlook were becoming readily available on the World Wide Web (WWW). The goal of the Drought Watch Section of the NDMC's website is to provide firsthand assessments using the SPI and also to link with other sites that provide information on snow pack, soil/crop moisture conditions, ground water and reservoir levels, stream flow, fire danger, and forecasts. Users can assemble the necessary data and informational products to assess current climate conditions and longer-range climate and water supply outlooks. This has been a very effective tool and is the most often visited section of the NDMC website.

In 1997, the formation of the MAP working group of the WDCC led to the development of a quarterly climate assessment report for the western United States. The purpose of this report was to provide an overview of current climate conditions and identify potential areas where drought conditions were likely to emerge in the months ahead. The MAP working group membership consists of a cross-section of state, regional and national interests from many different agencies. Some of the organizations involved in the WDCC MAP group represent the NDMC; Western Regional Climate Center; Colorado State Climatologist; Arizona Department of Water Resources; U.S. Department of Agriculture's (USDA) Agricultural Research Service and Natural Resources Conservation Service; National Oceanic and Atmospheric Administration's (NOAA) National Climatic Data Center, Climate Prediction Center, and National Weather Service; U.S. Geological Survey; and Joint Agricultural Weather Facility of USDA and NOAA.

The goal of the MAP working group is to develop an integrated drought monitoring system that provides timely recognition of the occurrence of drought to local, state, tribal, and federal officials responsible for implementing drought response and mitigation measures. The system also tries to track and report physical impacts during droughts, which helps others assess socio-economic impacts on various water users and economic sectors. The main product developed by the MAP group is a quarterly report called *Western Climate and Water Status*. During times of drought the group produces reports on a more frequent basis. An explanation of the report follows a discussion of how the report is generated.

Today's technology allows us to tap data resources that once took weeks or months to obtain. The WWW is the backbone of the MAP group's information and dissemination system. Many hard-copy reports in the climate arena are out of date by the time they reach a user's desk. In reality, reports put on the WWW are also out of date by the time they are put up on the web, but there is much less of a time lag. No other delivery tool lends itself to an assessment report like the Internet does. Users can be notified as soon as this report is available and they can download the product as needed.

The MAP group has undertaken the task of identifying and organizing literally hundreds of links dealing with climate and, more specifically, drought. This is an ever-evolving list as new sites are constantly being added. These sites give us timely access to relevant data and information products. It is also imperative, however, that these products are not used before analyzing the products and the source of data on which these products are based. This can be a rather time consuming task.

This process does allow for near real-time gathering of data and products across all agencies and at all levels of detail on a nationwide basis. To provide access to more timely monitoring information, a separate set of coordinating activities has been initiated by MAP to improve the flow and timeliness of climate and water condition information and to synthesize this information into products in an automated manner on a daily or weekly basis. Most of the product links are housed in the NDMC's *Drought Watch* section (http://enso.unl.edu/ndmc/watch) or at the Western Regional Climate Center's website (http://www.wrcc.sage.dri.edu/monitor/wdccmon.html).

Each quarter, a review of the products is done by the members of the MAP group. The most relevant products are gleaned from the various sites and are incorporated as either text or graphic information. This approach is subjective, but usually a consensus is reached that takes into account where the trouble spots are or may emerge in the future. One person takes the lead in drafting the report and all members of the MAP group have an opportunity to edit the report. The NDMC's communication specialist also edits the report for clarity before distribution. Final content edits and reviews are then incorporated into two formats: (1) a full-length, comprehensive web-embedded HTML document with hyperlinks to all relevant information located on the WDCC homepage (http://enso.unl.edu/wdcc/quarterly/index.html) and (2) a 2-page color briefing version created in a PDF format, which is available on the web and distributed to more than 400 people, including all members of Congress and the governors of the 18 western states and other relevant personnel.

The full report consists of an *Executive Summary*, a *Climate Recap* for the region (by month), *Water Supply Conditions* (snow pack, current and projected stream flow conditions, and reservoir levels), *Impacts* occurring or expected, *Special Conditions* when relevant (El Niño or La Niña events, for example), and *Future Forecasts*. The *Briefing Version* contains a condensed *Executive Summary*, areas experiencing *Dry* and/or *Wet* conditions, and an *Outlook* discussion. This product also contains two to four relevant maps/products depicting current conditions and/or expected conditions in the region.

This process has also highlighted a number of shortcomings and some unevenness in the level of accessibility to information; these need to be addressed. We see these from state to state, agency to agency, sector to sector, element to element, and so forth.

To help in policy or decision makers' resource allocation decisions, it would help to have timely and systematic reports of social, economic, and environmental impacts, in addition to the available climate data. Currently, the NDMC produces the closest product there is to a detailed national impacts report. *Drought in the U.S.* is produced monthly and located on the NDMC's website at http://enso.unl.edu/ndmc/impacts/us/usimpact.htm.

The MAP working group has been successful in bringing technical experts together across federal and state agencies to produce a quality text/graphic-based product that is timely and useful to a wide range of decision makers at all levels of government. The status of the WDCC (i.e., co-chaired by the Secretary of Agriculture and the Governor of New Mexico with representation from key federal agencies and functioning under the authority of the governors of western states) gave weight to the effort and encouraged cooperation from appropriate government entities in order to meet the MAP working group's tight time line.

The formation of the National Drought Policy Commission (NDPC) provides the opportunity to extend the geographical coverage of this report to include the entire United States (background on the NDPC is included in Wilhite, *Drought Preparedness in the United States: Recent Progress*, this volume). The severe drought that developed during the spring and summer of 1998 in the Southeast and the drought conditions that evolved in the Northeast during the fall and winter months of 1998–99 further emphasized the importance of routine national climate assessments. The NDMC will encourage the NDPC to implement a national integrated climate monitoring system that produces routine national climatic assessments.

5. Climate/Drought Indices

Climatic indices are important elements of any monitoring and assessment system because their purpose is to simplify complex interrelationships between many climate and climate-related parameters. Indices make it easier to communicate information about climate anomalies to diverse user audiences and allow scientists to quantitatively assess climate anomalies in terms of their intensity, duration, and spatial extent. This allows for the analysis of the historical occurrence of drought and its probability of recurrence. This information is extremely useful for planning and design applications in agriculture and numerous other sectors.

The most widely used drought index in the United States was developed by Palmer (1965). Palmer recognized the need for a better monitoring tool that could identify drought in terms of its intensity, duration, and spatial extent. Palmer's index became known as the Palmer Drought Severity Index (PDSI). Although there are several variations of the index, each variation has characteristics similar to the PDSI (Palmer, 1965; Karl and Knight, 1985; Heddinghaus and Sabol, 1991). Palmer based the PDSI on anomalies in the supply and demand concept of the water balance equation. Inputs into weekly or monthly calculations include precipitation, temperature, and the local antecedent soil moisture conditions. The data are standardized to account for regional differences so that the PDSI values can be compared from one location to another. Therefore, identical PDSI values, in theory, in the Midwest and Texas indicate the same severity of drought, even though actual rainfall deficiencies would be different at the two locations.

Weekly maps of a modified PDSI (Heddinghaus and Sabol, 1991) are produced by the Climate Prediction Center (CPC)/NOAA and are frequently used in assessment of agricultural conditions around the United States. The PDSI is also used in USDA policy decisions on requests for drought relief and by states as triggers for response actions as part of state drought plans. However, the PDSI has limitations that diminish its application and bring into question the practice of basing policy decisions solely on the PDSI. These limitations have been well documented (Alley, 1984; Karl and Knight, 1985; Smith et al., 1993; Willeke et al., 1994; Kogan, 1995; McKee et al., 1993; Guttman, 1998). The most significant limitations of the PDSI for monitoring drought include: (1) an inherent time scale that makes the PDSI better suited for monitoring agriculturally related impacts rather than longer-term hydrological impacts; (2) the tendency to treat all precipitation as rain so that snowfall, snow cover, and frozen ground are not accounted for, making real-time winter PDSI values of questionable reliability; (3) the tendency to ignore the natural lag between precipitation and runoff and the belief that no runoff occurs until the water capacities of the surface and subsurface soil layers are full, leading to an underestimation of runoff; and (4) a wide variance in the "extreme" and "severe" classifications of the PDSI values, depending on location in the country. If a drought index is going to be spatially comparable and useful for policy decisions, extreme and severe classifications must occur consistently and with low frequency (Guttman et al., 1992). An additional concern is that the PDSI does not do well in the mountainous west, especially since a majority of that region's precipitation falls during the winter as snowfall. The PDSI also can respond slowly to developing drought conditions and, once a region is in drought, the PDSI can retain values reflecting drought well after a climatological recovery from drought has occurred (McKee, 1996). All of these limitations reveal the importance of caution when using the PDSI for drought monitoring and policy decisions. The Standardized Precipitation Index (SPI) was developed to address some of the problems inherent in the PDSI.

McKee and his colleagues at Colorado State University (McKee et al., 1993 and 1995) designed the SPI to be a relatively simple, year-round index applicable to the water supply conditions important to Colorado and as a supplement to information provided by the PDSI and a second drought index, the Surface Water Supply Index (Shafer and Dezman, 1982). The SPI is based on precipitation alone. Its fundamental strength is that it can be calculated for a variety of time scales. This versatility allows the use of the SPI to monitor short-term water supplies, such as soil moisture important for agricultural production, and longer-term water resources such as ground water supplies, streamflow, and lake and reservoir levels. The ability to examine different time scales also allows droughts to be readily identified and monitored for the duration of the drought. Colorado has now used the SPI information as part of the climatic assessment done routinely by their Water Availability Task Force since 1994, including 1996, when drought affected portions of the state.

Calculation of the SPI for the specified time period for any location requires a long-term monthly precipitation data base with 30 years or more of data. The probability distribution function is determined from the long-term record by fitting a function to the data. The cumulative distribution is then transformed using equal probability to a normal distribution with a mean of zero and standard deviation of one so the values of the SPI are really in standard deviations (Edwards and McKee, 1997). A particular precipitation total for a specified time period is then identified with a particular SPI value consistent with probability. Positive SPI values indicate greater than median precipitation, while negative values indicate less than median precipitation. The magnitude of departure from zero represents a probability of occurrence so that decisions can be made based on this SPI value. Because SPI values fit a typical normal distribution, one can expect these values to be within one standard deviation approximately 68% of the time, within two standard deviations 95% of the time, and within three standard deviations 99% of the time. A related interpretation would be that a SPI value of less than –1.0 occurs 16 times in one hundred years and a SPI of less than –2.0 occurs 2–3 times in one hundred years.

McKee et al. (1993 and 1995) originally used an incomplete gamma distribution to calculate the SPI. Efforts are now in progress to standardize the SPI computing procedure so that common temporal and spatial comparisons can be made by SPI users (Guttman, 1998).

The SPI has a number of advantages over the PDSI. First, it is a simple index and is based only on precipitation. The PDSI calculations are complex (i.e., 68 terms are actually defined as part of the calculation procedure) (Soule, 1992). In spite of the complexity of the

PDSI, McKee (1996) believes that the main driving force behind the PDSI is precipitation. Second, the SPI is versatile. It can be calculated on any time scale, which gives the SPI the capability to monitor conditions important for both agricultural and hydrological applications. This versatility is also critical for monitoring the temporal dynamics of a drought, including its onset and end, which have typically been a difficult task for other indices. Third, because of the normal distribution of SPI values, the frequencies of extreme and severe drought classifications for any location and any time scale are consistent. McKee et al. (1993) suggest an SPI classification scale (table 1). An extreme drought according to this scale (SPI ≤–2.0) occurs approximately 2–3 times in 100 years, an acceptable frequency for water planning. Fourth, because it is based only on precipitation and not on estimated soil moisture conditions, as is the PDSI, the SPI is just as effective during the winter months.

Table 1. SPI Values

2.0 and above	extremely wet
1.50 to 1.99	very wet
1.00 to 1.49	moderately wet
–0.99 to 0.99	near normal
–1.00 to –1.49	moderately dry
–1.50 to –1.99	severely dry
–2.00 and less	extremely dry

Although developed for use in Colorado, the SPI can be applied to any location with a data set of 30 years or longer. Montana, Wyoming, New Mexico, South Carolina, and Nebraska have investigated or are using the SPI as part of their statewide efforts to monitor drought. The SPI is also used routinely at the national level by the NDMC and federal agencies. Researchers in Mexico, Costa Rica, Argentina, Brazil, Chile, Turkey, Hungary, South Africa, and Kenya have either considered or are using the SPI for projects in their respective countries.

The NDMC has created national maps of the SPI by climatic division for the continental United States since February 1996. The precipitation data set comes from CPC and the SPI values are calculated by the Western Regional Climate Center (WRCC). These are the same data used to create near real-time PDSI values used in weekly maps created by the CPC. The NDMC makes its maps available over the WWW, with links to other federal agencies. NDMC maps of the SPI are produced at 1-, 3-, 6-, and 12-month time scales as well as for the year to date. These maps are archived on the NDMC's website.

The NDMC's experience has been that the SPI more quickly detects emerging drought conditions than the PDSI, a characteristic that is extremely critical in the timely implementation of mitigation and response actions by individuals and government. A growing number of states are now using the SPI to trigger various drought-related actions. Additional research needs to be done to determine the relationships between SPI values and impacts in specific sectors.

6. Summary

Drought is an insidious natural hazard that is a normal part of the climate of virtually all regions. It should not be viewed as merely a physical phenomenon. Rather, drought is the result of an interplay between a natural event and the demand placed on water supply by human-use systems. Drought should be considered relative to some long-term average condition of balance between precipitation and evapotranspiration.

The three characteristics that differentiate one drought from another are intensity, duration, and spatial extent. Intensity refers to the degree of precipitation shortfall and/or the severity of impacts associated with the departure. Intensity is closely linked to the duration of the event. Droughts normally take two to three months to become established but may then persist for months or years, although the intensity and spatial character of the event will change from month to month or season to season. Droughts, unlike other natural hazards, can affect large areas and complicate assessment and response efforts.

Because of the slow-onset nature of drought, monitoring and early warning is an essential part of a comprehensive drought management plan. The development of an integrated climate/drought monitoring system in the United States has been recommended for some time. Recently, the development of the Internet and the WWW has provided the technology to improve information sharing on those critical elements of the hydrologic cycle required to monitor drought and water supply. The NDMC has taken advantage of this technology by developing a drought watch section on their website, with links to other agencies and organizations. The WDCC has provided the necessary support and motivation to develop a comprehensive regional drought watch system for the western states. This system can serve as a model for a national system in the United States that could be transferable to other regions. New indices, such as the SPI, have provided an important tool in assessing climate conditions and initiating mitigation and response actions.

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