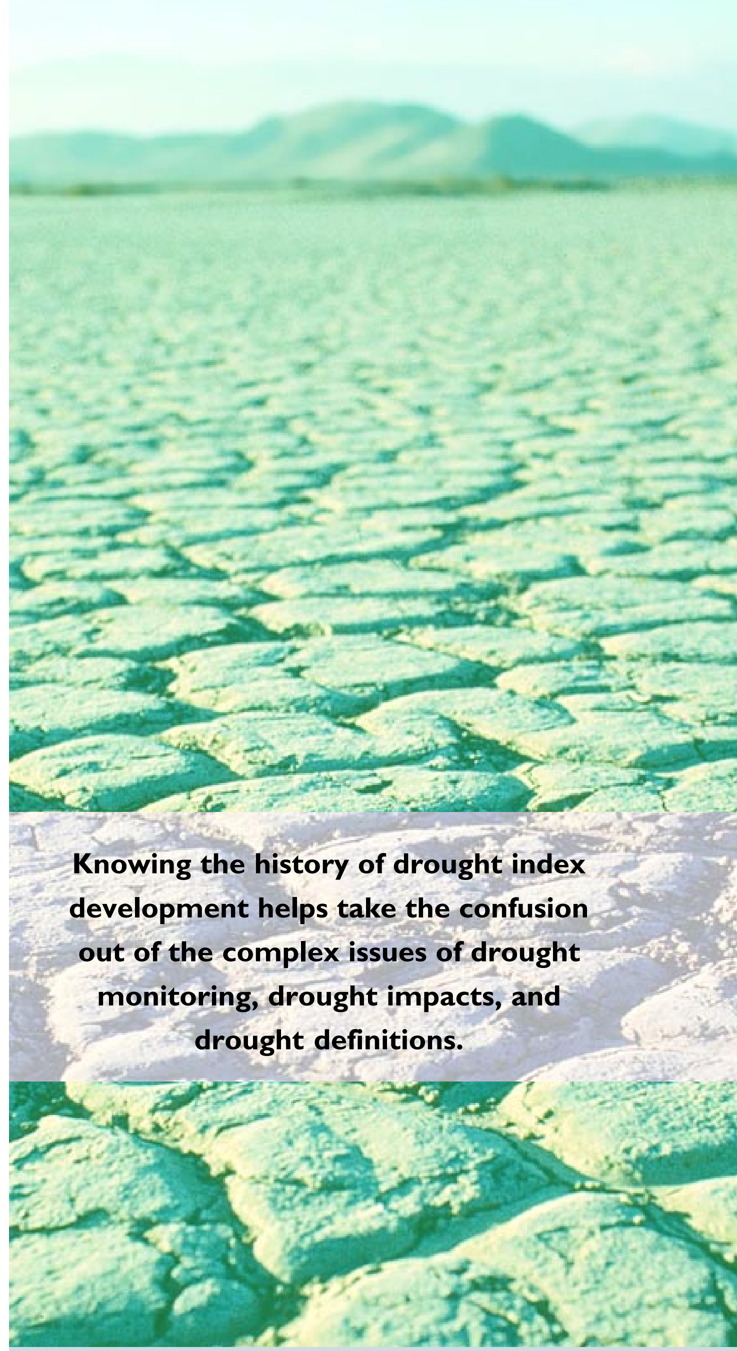
# A Review of Twentieth-Century Drought Indices Used in the United States

BY RICHARD R. HEIM JR.



**Knowing the history of drought index development helps take the confusion out of the complex issues of drought monitoring, drought impacts, and drought definitions.**

Drought is a recurring phenomena that has plagued civilization throughout history. It affects natural habitats, ecosystems, and many economic and social sectors, from the foundation of civilization—agriculture—to transportation, urban water supply, and the modern complex industries. The wide variety of sectors affected by drought, its diverse geographical and temporal distribution, and the demand placed on water supply by human-use systems make it difficult to develop a single definition of drought.

The American Meteorological Society (1997) groups drought definitions and types into four categories: meteorological or climatological, agricultural, hydrological, and socioeconomic. A prolonged (e.g., of several months or years duration) *meteorological drought*—the atmospheric conditions resulting in the absence or reduction of precipitation—can develop quickly and end abruptly (in some cases, the transition can occur almost literally overnight). Short-term (i.e., a few weeks duration) dryness in the surface layers (root zone), which occurs at a critical time during the growing season, can result in an *agricultural drought* that severely reduces crop yields, even though deeper soil levels may be saturated. Hot temperatures, low relative humidity, and desiccating winds often add to the impact of the lack of rainfall (Condra 1944). The onset of an agricultural drought may lag that of a meteorological drought, depending on the prior moisture status of the surface soil layers. Precipitation deficits over a prolonged period that affect surface or subsurface water supply, thus reducing streamflow, groundwater, reservoir, and lake levels, will result in a *hydrological drought*, which will persist long after a meteorological drought has ended. *Socioeconomic drought* associates the supply and demand of some economic good with elements of meteorological, agricultural, and hydrological

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drought. The relationship between the different types of drought is complex. For example, streamflow is the key variable to analyze in describing droughts for many water supply activities such as hydropower generation, recreation, and irrigated agriculture where crop growth and yield are largely dependent on water availability in the stream. Consequently, drought has been defined by the international meteorological community in general terms as a "prolonged absence or marked deficiency of precipitation," a "deficiency of precipitation that results in water shortage for some activity or for some group," or a "period of abnormally dry weather sufficiently prolonged for the lack of precipitation to cause a serious hydrological imbalance" (World Meteorological Organization 1992; American Meteorological Society 1997).

Some numerical standard is needed for comparing measures of drought from region to region, as well as for comparing past drought events. However, the considerable disagreement that exists about the definition of drought makes it impossible to devise a universal drought index. Furthermore, drought's characteristics and the wide range of economic sectors on which it has an impact make its effects difficult to quantify. Because of the complexity of drought, no single index has been able to adequately capture the intensity and severity of drought and its potential impacts on such a diverse group of users.

The American Meteorological Society (1997) suggests that the time and space processes of supply and demand are the two basic processes that should be included in an objective definition of drought and, thus, in the derivation of a drought index. The World Meteorological Organization defines a drought index as "an index which is related to some of the cumulative effects of a prolonged and abnormal moisture deficiency" (World Meteorological Organization 1992). Friedman (1957) identified four basic criteria that any drought index should meet: 1) the timescale should be appropriate to the problem at hand; 2) the index should be a quantitative measure of large-scale, long-continuing drought conditions; 3) the index should be applicable to the problem being studied; and 4) a long accurate past record of the index should be available or computable. A fifth criteria should be added for indices used in operational drought monitoring: 5) the index should be able to be computed on a near-real-time basis. For example, indices that are useful for long-term paleoclimatic studies (e.g., indices based on glaciological and alluvial evidence, oceanic and lake sediments, tree-ring and pollen analysis, or proxy evidence such as historical documents and annual crop yield) would not be applicable for the operational monitoring of drought because of the nature of paleoclimatic indices and the difficulty involved in collecting paleoclimatic data on a real-time operational basis. There are only a few cases (e.g., the streamflow records of Egypt's Nile River) where indices useful in paleoclimatic studies are available on an operational basis.

Many quantitative measures of drought have been developed in the United States, based on the sector and location affected, the particular application, and the degree of understanding of the phenomena. The complex water balance model developed by W. Palmer in the mid-twentieth century was a turning point in the evolution of drought indices. While an improvement over simple early twentieth-century measures, the Palmer Index suffers from some inherent weaknesses (these weaknesses will be discussed later). Post-Palmer solutions include modern indices, such as the Surface Water Supply Index and the Standardized Precipitation Index, and the Drought Monitor. Table 1 gives an overview of the major twentieth-century U.S. drought indices herein reviewed. By focusing on the evolution of U.S. drought indices, this paper provides insight into how our understanding of drought has changed during the past hundred years.

**EARLY DROUGHT INDICES.** Common to all types of drought is the fact that they originate from a deficiency of precipitation that results in water shortage for some activity or for some group (Wilhite and Glantz 1985). Reliable rainfall observations became available about two centuries ago, and as a result, practically all drought indices and drought definitions included this variable either singly or in combination with other meteorological elements (World Meteorological Organization 1975a).

Early meteorological drought definitions incorporated some measure of precipitation over a given period of time (Tannehill 1947; World Meteorological Organization 1975a; Wilhite and Glantz 1985). A drought would exist if the criteria defining the drought were met, and the index would then be a measure of the drought's duration and/or intensity.

Hydrological drought indices were based largely on streamflow, as this variable summarizes and is the by-product of essentially every hydrometeorological process taking place in watersheds and river basins. In hydrologic studies involving the rate of flow in streams, it is important to distinguish between the two components of total flow: direct runoff and base flow (Linsley et al. 1958). *Direct* or *surface runoff* is water that travels over the ground surface to a channel. It

**Table 1. Major drought indices discussed in this paper.**

| Index | Year introduced | Variables analyzed; application |
|---|---|---|
| Munger's Index | 1916 | Length of period without 24-h precipitation of 1.27 mm; daily measure of comparative forest fire risk |
| Kincer's Index | 1919 | 30 or more consecutive days with less than 6.35 mm of precipitation in 24 h; seasonal distribution maps |
| Marcovitch's Index | 1930 | Temperature and precipitation; climatic requirements of the bean beetle |
| Blumenstock's Index | 1942 | Length of drought in days, where drought terminated by occurrence of 2.54 mm of precipitation in 48 h; short-term drought |
| Antecedent Precipitation Index | 1954 | Precipitation; a reverse drought index used for flood forecasting |
| Moisture Adequacy Index | 1957 | Precipitation and soil moisture; agricultural drought |
| Palmer's Index (PDSI and PHDI) | 1965 | Precipitation and temperature analyzed in a water balance model; comparison of meteorological and hydrological drought across space and time |
| Crop Moisture Index | 1968 | Precipitation and temperature analyzed in a water balance model; agricultural drought |
| Keetch–Byram Drought Index | 1968 | Precipitation and soil moisture analyzed in a water budget model; used by fire control managers |
| Surface Water Supply Index | 1981 | Snowpack, reservoir storage, streamflow, and precipitation; computed primarily for western river basins; statistical properties not well analyzed or understood |
| Standardized Precipitation Index | 1993 | Precipitation; allows measurement of droughts and wet spells in terms of precipitation deficit, percent of "normal," probability of nonexceedance, and SPI at multiple simultaneous timescales with potentially different behavior at all of them |
| Vegetation Condition Index | 1995 | Satellite AVHRR radiance (visible and near-IR); measures "health" of vegetation |
| Drought Monitor | 1999 | Integrates several drought indices and ancillary indicators into a weekly operational drought-monitoring map product; multipurpose |

reaches the stream soon after its occurrence as rainfall and appears as the crest point in a hydrograph. *Base flow* results from the discharge of groundwater into the stream where the water table intersects the stream channels of the basin. Base flow is also referred to as *groundwater flow* and *dry-weather flow* (Linsley et al. 1958) and appears as the recession point on a hydrograph. Drought studies utilizing streamflow data have relied on base flow measurements or the mean flow over some period (e.g., monthly or annual flows) to average out the direct runoff crests (see, e.g., Yevjevich 1967; Dracup et al. 1980; Frick et al. 1990).

During the first decade of the twentieth century, the U.S. Weather Bureau identified drought as occurring during any period of 21 or more days with rainfall 30% or more below normal for the period (Henry

1906; Steila 1987). A drought measure frequently used at that time was the accumulated precipitation deficit, or the accumulated departure from normal. Other examples of early criteria include the following:

1) 15 consecutive days with no rain,
2) 21 days or more with precipitation less than one-third of normal,
3) annual precipitation that is less than 75% of normal,
4) monthly precipitation that is less than 60% of normal, and
5) any amount of rainfall less than 85% of normal.

As late as 1957, Friedman used annual rainfall as his drought index in a study of drought in Texas. Similar criteria have been employed in other countries:

1) Britain: 15 consecutive days with less than 0.25 mm (0.01 in.) [or 1.0 mm (0.04 in.)];
2) India: rainfall half of normal or less for a week, or actual seasonal rainfall deficient by more than twice the mean deviation;
3) Russia: 10 days with total rainfall not exceeding 5 mm (0.20 in.);
4) Bali: a period of 6 days without rain; and
5) Libya: annual rainfall that is less than 180 mm (7 in.).

Most of these definitions/indices were valid only for their specific application in their specific region. Indices developed for one region may not be applicable in other regions because the meteorological conditions that result in drought are highly variable around the world. Indices developed to measure the intensity of meteorological drought, for instance, were inadequate for agricultural, hydrological, or other applications.

These deficiencies were recognized early (see, e.g., Abbe 1894; Henry 1906). The problems with developing an agricultural drought index, for example, include consideration of vegetation, soil type (which determines soil moisture capacity), antecedent soil moisture, and evapotranspiration as influenced by wind speed and the temperature and humidity of the air. Many of these climatic elements were not widely measured, or could not be incorporated into a drought index. For example, Abbe (1894) noted: "From an agricultural point of view, a drought is not merely a deficiency of rainfall, but a deficiency of water available for the use of the growing crops. . . . Thus a drought affecting agriculture is a complex result of many considerations. . . . Therefore, both from an agricultural and engineering point of view, it is impracticable [sic] to define the intensity of a drought in general and exact terms." In the U.S. Weather Bureau's Bulletin Q: Climatology of the United States, Henry (1906) concluded that, "In general, climatological statistics alone fail to give a sufficient accurate conception either of the duration or intensity of [agricultural] drought. Supplementary observations upon the condition of vegetation in each locality are especially needed."

During the first half of the twentieth century, scientists focused their efforts on addressing these inadequacies, as well as continuing to develop drought indices relevant to the specific application being considered.

Munger (1916) developed an objective measure of the comparative forest fire risk from year to year and region to region. After determining that the frequency of soaking rains is the factor with the greatest influence on the fire hazard in the Pacific Northwest,

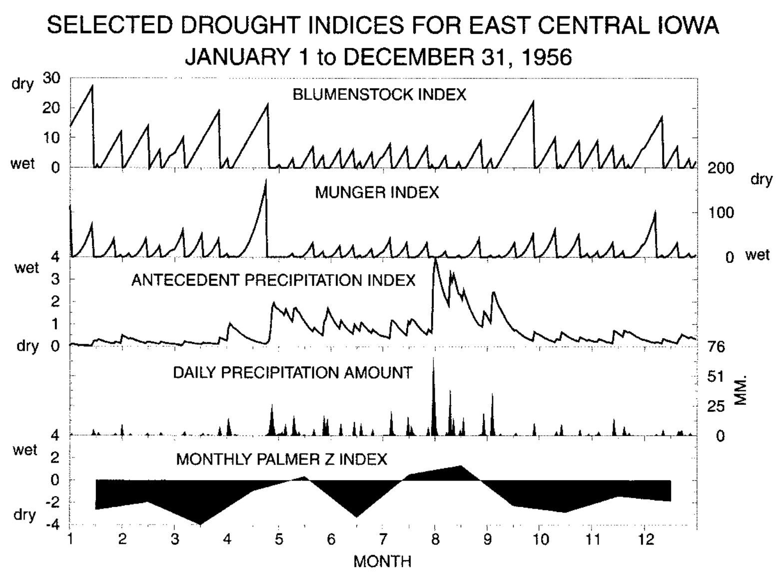


**FIG. 1. Comparison of daily precipitation amount, three daily drought indices (the Blumenstock and Munger Indices and the API), and the monthly Palmer *Z* Index for east-central Iowa for 1 Jan–31 Dec 1956. Both the Blumenstock (1942) and Munger (1916) Indices are based on the length of the drought (in days), while the API (McQuigg 1954; Waggoner and O'Connell 1956) incorporated both the amount and timing of precipitation for flood forecasting and is, thus, a reverse drought index. These three indices are best suited for use on a short (daily to multimonthly) timescale.**

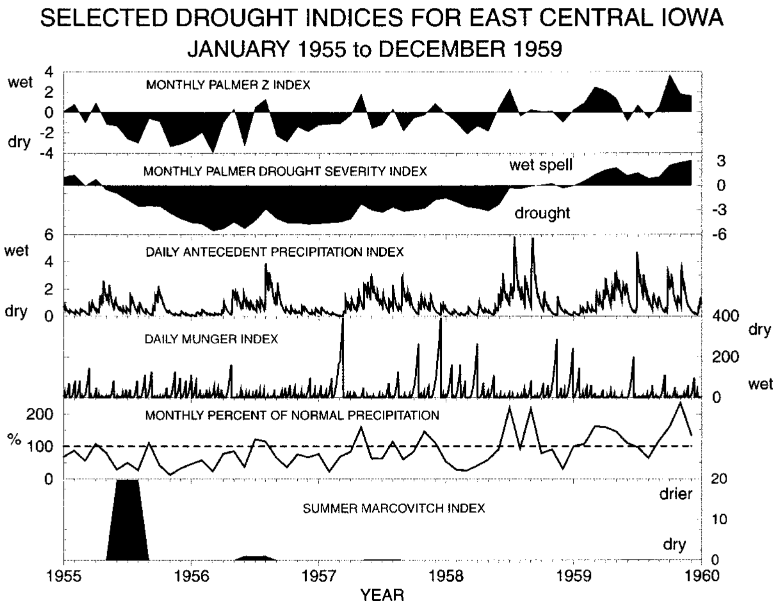


**FIG. 2. Comparison of two daily drought indices (the Munger Index and the API), the summer Marcovitch Index, monthly percent of normal precipitation, and two monthly Palmer indices (the *Z* Index and the PDSI) for east-central Iowa for 1 Jan 1955–31 Dec 1959. The computational method and purpose can result in quite disparate indices, as seen in this figure. The Munger (1916) Index is based on the length of the drought (in days), the API (McQuigg 1954; Waggoner and O'Connell 1956) incorporated both the amount and timing of precipitation for flood forecasting, and the Marcovitch (1930) Index incorporated temperature and precipitation into a seasonal index. The Palmer (1965) indices, computed on a monthly timescale here, are based on a water budget soil model and show short-term (*Z* Index) and cumulative long-term (PDSI) drought and wet spell conditions.**

Munger used, as his drought index, the number of consecutive days where 24-h rainfall is less than 1.27 mm (0.05 in.). He noted that the parching effect of droughts on forest vegetation is not directly proportional to their length. He assumed that the intensity of droughts increases as the square of their duration. Munger devised a graphical technique to represent the intensity of the drought (Figs. 1 and 2; cf. Munger's Index to several other indices). The technique used the area of a right triangle, whose height and base were both proportional to the duration of the drought. Expressed mathematically,

$$\text{severity of drought} = \tfrac{1}{2} L^2,$$

where $L$ is the length of the drought in days.

Kincer (1919) prepared, for the first time, a series of much needed maps and charts showing the seasonal distribution of precipitation, and climatologies of the average annual number of days with precipitation of various intensities, in the contiguous United States. Included were maps showing the frequency of subnormal precipitation (i.e., droughts) for the United States east of the Rockies for the warm season (March–September). Kincer defined a drought as 30 or more consecutive days with less than 6.35 mm (0.25 in.) of precipitation in 24 h.

In a study of the climatic requirements of the bean beetle in the eastern United States, Marcovitch (1930) devised an equation incorporating both temperature and precipitation to compute a drought index:

$$\text{drought index} = \tfrac{1}{2}(N/R)^2,$$

where $N$ is the total number of two or more consecutive days above 32.2°C (90°F), and $R$ is the total summer rainfall for the same months. The Marcovitch Index, illustrated in Figs. 2 and 3, is a seasonal index best used in retrospective studies.

Blumenstock (1942) applied probability theory to compute drought frequencies in a climatic study. For his index, he used the length of the drought in days, where a drought was considered terminated by the occurrence of at least 2.54 mm (0.10 in.) of precipitation in 48 h or less. The Blumenstock Index is compared to several other indices in Fig. 1. Both Blumenstock's and Munger's indices are best used to measure short-term drought.

Efforts to measure depletion of soil moisture focused on evaporation, and measurement of the amount of moisture used by plants focused on transpiration. According to Thornthwaite (1931), evaporation and transpiration [or collectively, evapotranspiration (ET)] depend on solar radiation, wind speed, humidity, nature of vegetation, and condition of the soil, with solar radiation being the dominant factor. However, since direct measurements of solar radiation are not generally available, it was found that the mean daily temperature, latitude, and the time of year could be used to approximate the amount of water loss to the atmosphere by evaporation when it is assumed that there is an adequate supply of moisture in the soil for the vegetation at all times. This measure is called potential evapotranspiration (PE). The difference be-

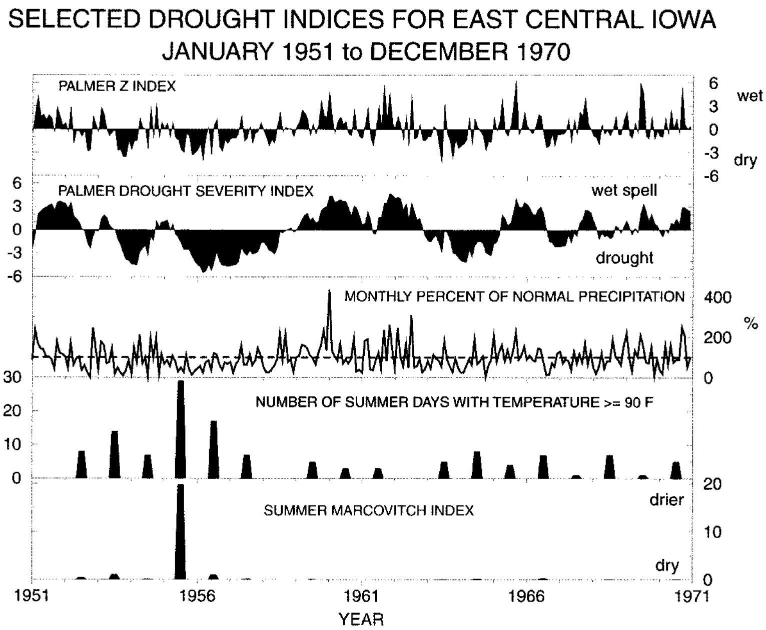


**Fig. 3. Comparison of the summer Marcovitch Index and its components to two monthly Palmer indices (the *Z* Index and the PDSI) for east-central Iowa for 1 Jan 1951–31 Dec 1970. The Marcovitch (1930) Index was derived to determine the climatic requirements of the bean beetle in the eastern United States and incorporated temperature and precipitation into a seasonal index. This index captures the mid-1950s drought in this part of the Midwest well, but the temperature component dominates and its scale and temporal frequency make it less suited for operational drought monitoring than the Palmer (1965) indices.**

tween actual and potential evapotranspiration depends on the availability of moisture in the soil. If adequate soil moisture is available, actual evapotranspiration equals potential evapotranspiration; otherwise, it is less.

With this foundation, Thornthwaite (1931) developed the precipitation effectiveness index, which is the sum of the 12 monthly precipitation effectiveness ratios, where the monthly effectiveness ratio is the monthly precipitation divided by the monthly evaporation. Thornthwaite (1948) also proposed using precipitation minus evapotranspiration as a drought index.

It should be pointed out that Thornthwaite's work furthered the development of drought indices, but he, along with Köppen and others, also did much to lay the groundwork for the modern climate classification system. As noted by the World Meteorological Organization (1975a), a distinction should be made between *drought* and *aridity*. Aridity is usually defined in terms of low-average precipitation, available water, or humidity and, setting aside the possibility of climatic change, is a permanent climatic feature of a region. Drought, on the other hand, is a temporary feature in the sense that, considered in the context of variability, it is experienced only when precipitation falls appreciably below normal. Aridity is, by definition, restricted to regions of low precipitation, and usually of high temperature, whereas drought is possible in virtually any precipitation or temperature regime. With this distinction in mind, Thornthwaite's two indices discussed above are better classified as climatological aridity indices rather than drought indices.

Thornthwaite's work prompted van Bavel and Verlinden (1956) to develop the concept of an agricultural drought day, a period of 1 day during which a drought condition exists (i.e., a day on which the available soil moisture is zero). They estimated soil moisture conditions using daily precipitation and evapotranspiration (computed using Penman's formula, which incorporated solar radiation, sunshine duration, air temperature, relative humidity, and wind speed). Dickson (1958) used the drought-day concept, but experimented with a different way of computing evapotranspiration (i.e., making it proportional to the total moisture content of the soil). His methodology resulted in a computed agricultural drought-day quantity that was considerably less (by up to 55%) than the method used by van Bavel and Verlinden.

McQuigg (1954) and Waggoner and O'Connell (1956) incorporated both the amount and timing of precipitation in their Antecedent Precipitation Index (API). Originally designed to estimate soil moisture content for use in flood forecasting, the API was computed on a daily basis by multiplying the index for the previous day by a factor, usually 0.90. If rain occurred on a day, the amount of rainfall observed was added to the index (see Figs. 1 and 2). Snowfall was included on the day it melted. They obtained good results for the eastern and central United States. Iowa corn yields were poor when the API dropped below 0.10 and in the wet years when it failed to go below 0.50 during mid-May to mid-August.

A drought index for corn—the "moisture stress day"—was developed in the 1960s (World Meteorological Organization 1975a). Calculation of the moisture stress day was based on PE and available soil water capacity. A moisture stress day (i.e., corn plants lost turgor) occurred if 1) PE exceeded 6.4 mm (0.25 in.) day$^{-1}$ when soil water was below 85% of available capacity, or 2) PE exceeded 5.1 mm (0.20 in.) day$^{-1}$ when soil water was below 50% of capacity, or 3) PE exceeded 1.3 mm (0.5 in.) day$^{-1}$ when soil water was less than 10% of available capacity.

Meanwhile, Thornthwaite and others developed the water budget accounting method to keep track of soil moisture. Various assumptions were made about soil moisture field capacity, and monthly values of precipitation and potential evapotranspiration were used. They emphasized the need to base the determination of drought severity on a comparison of water need with water supply in individual years. "We cannot define drought only as a shortage of rainfall," they said, "because such a definition would fail to take into account the amount of water needed. Furthermore, the effect of a shortage of rainfall depends on whether the soil is moist or dry at the beginning of the period. [Agricultural] drought does not begin when rain ceases but rather only when plant roots can no longer obtain moisture in needed amounts" (Thornthwaite and Mather 1955).

One attempt to address these needs was the idea of "moisture adequacy." This index, developed by McGuire and Palmer (1957) as an outgrowth from the concept of potential evapotranspiration, compared a location's moisture need to the actual moisture supply (rainfall plus available soil moisture). The moisture adequacy index is expressed as a percentage ratio of the actual moisture supply to the moisture need, where 100% indicates the supply is sufficient to meet the need. They plotted a map of these index values to show the general spatial pattern of drought during 1957 in the eastern United States.

As seen above, drought identification and evaluation procedures slowly evolved during the first half of the twentieth century from simplistic approaches that considered the phenomenon to be a rainfall deficiency, to problem-specific models of limited applicability. The stage was set for the development of a more sophisticated technique to quantitatively appraise what Steila (1987) termed the total environmental moisture status.

## PALMER'S DROUGHT INDEX.

In 1965, W. Palmer published his model for a drought index that incorporated antecedent precipitation, moisture supply, and moisture demand (based on the pioneering evapotranspiration work by Thornthwaite) into a hydrologic accounting system (Palmer 1965). He used a two-layered model for soil moisture computations and made certain assumptions concerning field capacity and transfer of moisture to and from the layers. These assumptions include the following: the top soil layer ("plough layer") has a field capacity of 1 in. (2.54 cm), moisture is not transferred to the bottom layer ("root zone") until the top layer is saturated, runoff does not occur until both soil layers are saturated, and all of the precipitation occurring in a month is utilized during that month to meet evapotranspiration and soil moisture demand or be lost as runoff. Palmer applied what he called Climatologically Appropriate for Existing Conditions (CAFEC) quantities to normalize his computations so he could compare the dimensionless index across space and time. This procedure enables the index to measure abnormal wetness (positive values) as well as dryness (negative values), with persistently normal precipitation and temperature theoretically resulting in an index of zero in all seasons in all climates. The term "Palmer Index" refers collectively to three indices that have come to be known as the PDSI, PHDI, and the *Z* Index.

The computation of Palmer's indices consists of the following steps:

1) Carry out a monthly hydrologic accounting for a long series of years using five parameters: precipitation, evapotranspiration, soil moisture loss and recharge, and runoff. Potential and actual values are computed for the last four. Palmer used monthly averages, but other timescales (such as weeks or days) can be used as well. Means of the potential and actual values for these parameters are computed over a calibration period that is usually, but not necessarily, the data period of record.
2) Summarize the results to obtain coefficients (of evapotranspiration, recharge, runoff, and loss) that are dependent on the climate of the location being analyzed. These coefficients are computed by dividing the mean actual quantity by the mean potential quantity.
3) Reanalyze the series using the derived coefficients to determine the amount of moisture required for "normal" weather during each month. These normal, or CAFEC, quantities are computed for each of the parameters listed in step 1).
4) Compute the precipitation departure (precipitation minus CAFEC precipitation) for each month, then convert the departures to indices of moisture anomaly. This moisture anomaly index has come to be known as the Palmer *Z* Index and reflects the departure of the weather of a particular month from the average moisture climate for that month,

regardless of what has occurred in prior or subsequent months.

5) Analyze the index series to determine the beginning, ending, and severity of the drought periods. In Palmer's computations, the drought severity for a month depends on the moisture anomaly for that month *and* on the drought severity for the previous and subsequent months. His methodology involves computing, for each month, three intermediate indices (X1, X2, and X3) and a probability factor, which are explained below.

There is a lag between the time that the drought-inducing meteorological conditions end and the environment recovers from a drought. Palmer made this distinction by computing a *meteorological* drought index and a *hydrological* drought index. In his effort to create the meteorological drought index [which has come to be known as the Palmer Drought Severity Index, (PDSI)], Palmer expressed the beginning and ending of drought (or wet) periods in terms of the *probability* that the spell has started or ended. A drought or wet spell is definitely over when this probability reaches or exceeds 100%, but the drought or wet spell is considered to have ended the *first month* when the probability became greater than 0% and then continued to remain above 0% until it reached 100%. During the period of "uncertainty" when an existing drought (or wet spell) may or may not be over (i.e., when the probability is greater than zero but less than 100%), the model computes index values for an incipient wet spell (X1), an incipient drought (X2), and the existing spell (X3). The X3 term can refer to either an established drought or wet spell. The model selects one of these terms (X1, X2, or X3) for the PDSI in a backstepping procedure, with the term selected depending on the probability that the established spell is over (e.g., X1 is chosen for the PSDI if the probability indicates the existing drought has ended, X2 is chosen if the existing wet spell has ended, and X3 is chosen if the probability does not reach 100%). The value of the "established spell" (X3) term changes more slowly than the values of the "incipient" (X1 and X2) terms. The X3 term is the index for the long-term hydrologic moisture conditions and has come to be known as the Palmer Hydrological Drought Index (PHDI).

This backstepping procedure of ending droughts or wet spells cannot be satisfactorily used for real-time calculations of PDSIs (i.e., operational PDSIs) since one cannot know in advance whether a few months of wet or dry weather are the beginning of a new spell of wet or dry weather or merely a temporary interruption of the current drought or wet spell (Karl 1986). The National Weather Service (NWS) incorporated the probability factor in a modification of the PDSI in the 1990s (Heddinghaus and Sabol 1991). The NWS modification (referred to here as the PMDI or simply PDI) allows computation of the PDSI operationally by taking the sum of the wet and dry terms after they have been weighted by their probabilities (*P* and 100% –*P*, where *P* = the probability that the spell is over).

At the time of its introduction, Palmer's procedure was hailed as "the most satisfactory solution to the problem of combining precipitation and temperature as predictor variables" (Julian and Fritts 1968). The Palmer Index became widely used in the United States and has been applied to other areas of the world (World Meteorological Organization 1975a; Kogan 1995; Hu and Willson 2000). As part of a PHDI study to aid planners during recov-

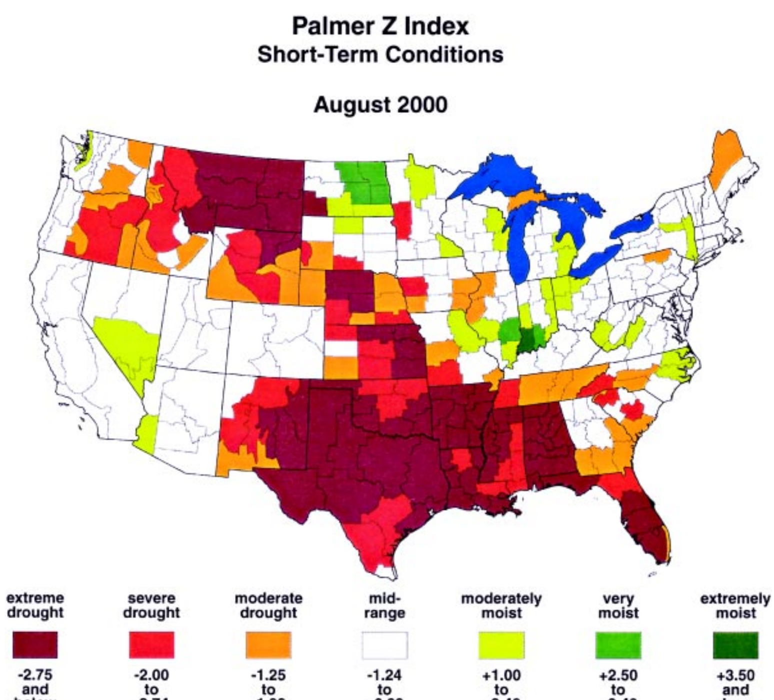


**Fig. 4. The Palmer *Z* Index for Aug 2000, illustrating the extremely dry conditions that occurred during that month from the southeast and southern plains to the northwestern United States.**

ery from severe droughts, Karl et al. (1986, 1987) computed the precipitation required to end or ameliorate an existing drought, and the climatological probability of receiving at least this required amount of precipitation, for the 344 climate divisions of the contiguous United States. Figures 1–7 illustrate how Palmer's indices can be used to compare droughts through time and space, and how his indices compare to other drought indices.

The Palmer Index was a landmark in the development of drought indices. However, it is not without limitations. The index was specifically designed to treat the drought problem in semiarid and dry subhumid climates where local precipitation is the sole or primary source of moisture (Doesken et al. 1991). Palmer himself cautioned that extrapolation beyond these conditions may lead to unrealistic results (Palmer 1965; Guttman 1991). During the last 30 years, several scientists have evaluated the model as applied under different climate regimes and have expressed concerns with some of the model's assumptions. These concerns fall into two broad categories: the use of water balance models in general, and Palmer's model in particular.

Alley (1984) expressed concerns regarding how water balance models treat potential evapotranspiration, soil moisture, runoff, distribution of precipitation, and evapotranspiration within a month or week, and how they fail to consider seasonal or annual changes in vegetation cover and root development. His evaluation was also critical of the Palmer model for failing to incorporate a lag to account for the delay between the generation of excess water and its appearance as runoff, and for making no allowance for the effect of snowmelt or frozen ground. He was also concerned about the arbitrary designation of the drought severity classes (see Table 2) and the transition index values indicating an end to an established drought or wet spell.

Palmer tried to normalize his index so it could be comparable between different locations and seasons. However, because the weighting factor Palmer used was based on results from only nine climatic divisions and on data aggregated on the annual level, his index, in fact, is not spatially comparable across the contiguous United States (Alley 1984; Guttman et al. 1992; Guttman 1997) nor directly comparable between months (Alley 1984). Concern was raised about the abrupt transition between wet and dry spells that results from the backstepping procedure and switching among the X1, X2, and X3 in the assignment of the PDSI values. This methodology may result in asym-

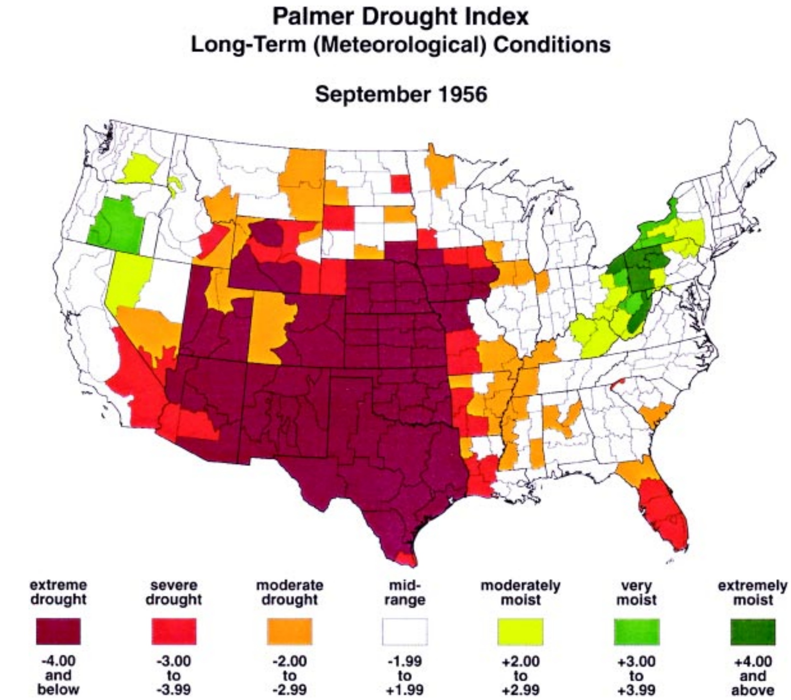


**FIG. 5. The PMDI showing the cumulative long-term drought conditions for Sep 1956. During this month just under 40% of the contiguous United States experienced severe to extreme drought.**

**TABLE 2. Palmer drought index categories (from Palmer 1965).**

| Moisture category | PDSI |
|---|---|
| Extremely wet | ≥ 4.00 |
| Very wet | 3.00 to 3.99 |
| Moderately wet | 2.00 to 2.99 |
| Slightly wet | 1.00 to 1.99 |
| Incipient wet spell | 0.50 to 0.99 |
| Near normal | 0.49 to −0.49 |
| Incipient drought | −0.50 to −0.99 |
| Mild drought | −1.00 to −1.99 |
| Moderate drought | −2.00 to −2.99 |
| Severe drought | −3.00 to −3.99 |
| Extreme drought | ≤− 4.00 |

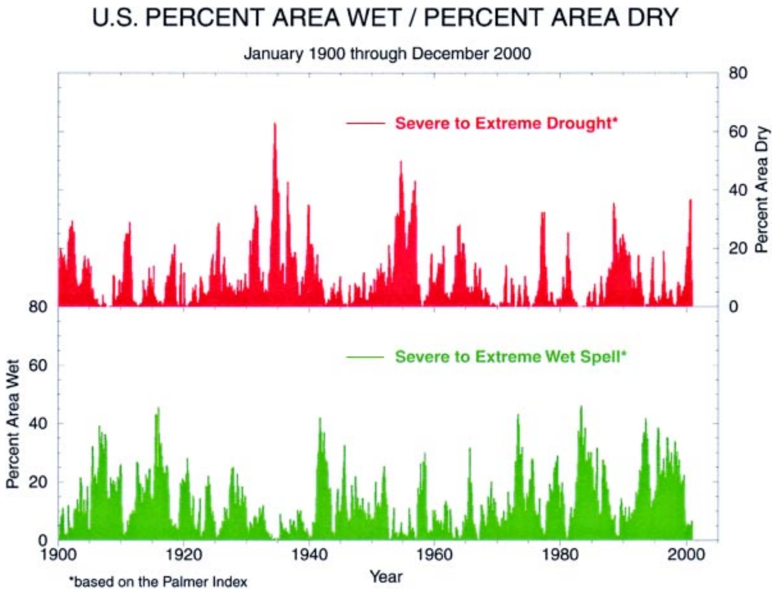


**Fig. 6. The percent area of the contiguous United States experiencing monthly (top) severe to extreme long-term drought and (bottom) severe to extreme long-term wet conditions during the twentieth century, based on the PMDI. The major (national scale) drought episodes stand out, with drought reaching its greatest extent during the "dust bowl" years of the 1930s. At its peak, drought covered 63% of the nation during Jul 1934, with a secondary peak of about 43% during Aug 1936. The 1950s was another decade of drought, peaking at about 50% in Sep 1954 and 43% in Dec 1956. While significant droughts occurred in the 1980s and 1990s, severe to extreme wet spells were more prevalent. Similar time series could be created for other combinations of wet and dry Palmer categories.**

metrical and bimodal statistical distributions of the PDSI (and possibly the PHDI) index values (Alley 1984; Guttman 1991).

Sensitivity studies have found that the value of the PDSI is highly dependent on 1) the weighting factor used to make it comparable between different months and regions, 2) the value specified for the available water capacity in the soil (Karl 1983), as well as 3) the calibration period used to compute the CAFEC quantities (Karl 1986), with longer calibration periods providing more consistent estimates of the CAFEC quantities and index values. If the calibration period is changed, the Palmer indices for the entire period of record should be recomputed to maintain consistency through time. For comparative spatial studies, the same calibration period should be used for all locations. Guttman (1991) found that 1) the period of time required for the PHDI to reflect actual rather than artificial initial conditions could be more than 4 yr, and 2) the effects of temperature anomalies are insignificant compared to the effects of precipitation anomalies. However, in a study of the PDSI over the central United States, Hu and Willson (2000) determined that the PDSI can be equally affected by temperature and precipitation when both have similar magnitudes of anomalies, and reconstructions of PDSI based solely on precipitation

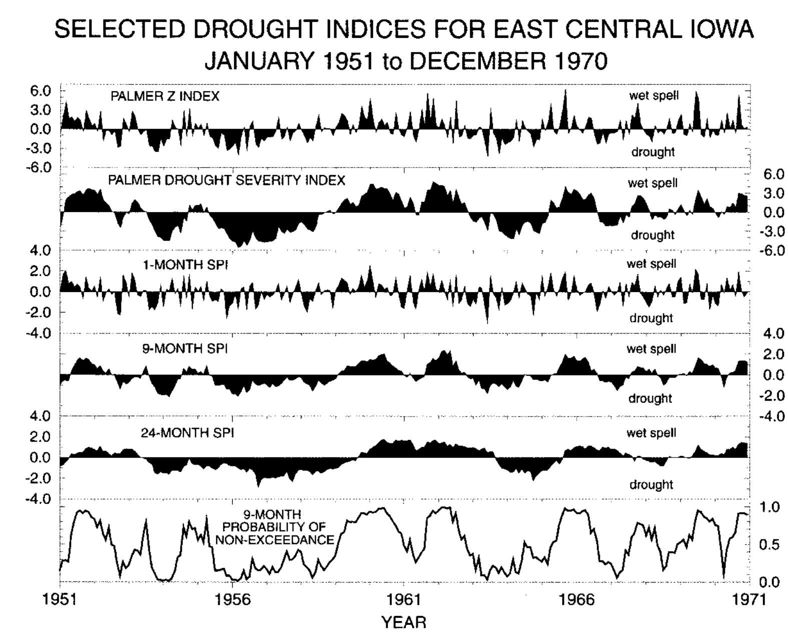


**Fig. 7. Comparison of two monthly Palmer indices (the *Z* Index and the PDSI) to several SPI products for east-central Iowa for 1 Jan 1951–31 Dec 1970. Both the 1-month SPI and the Palmer *Z* Index measure short-term (i.e., monthly) drought. The 9-month SPI corresponds approximately to the PDSI. The versatility of the SPI is illustrated here by its ability to chart longer-scale drought (24-month SPI) and to put precipitation deficits into a probabilistic perspective. The utility of the particular index used depends on the application and what the user is trying to show. One cannot make a blanket statement that a particular index is better, overall, than another index.**

could lead to ambiguous conclusions about past climatic variations.

Since its inception, the Palmer Index has become widely used by a variety of people (hydrologists, foresters, field meteorologists, economists, policy decision makers, news media, private consultants, and researchers) as a tool to monitor and assess long-term meteorological drought and wet spell conditions. As pointed out by the National Drought Mitigation Center (see online at http://enso.unl.edu/ndmc/) and Willeke et al. (1994), it is most effective when applied to the measurement of impacts sensitive to soil moisture conditions, such as in agriculture, and it has also been used to start or end drought response actions.

Three years after the introduction of his drought index, Palmer (1968) introduced a new drought index based on weekly mean temperature and precipitation, as an outgrowth of his PDSI work. This Crop Moisture Index (CMI) was specifically designed as an agricultural drought index and depends on the drought severity at the beginning of the week and the evapotranspiration deficit or soil moisture recharge during the week. It measures both evapotranspiration deficits (drought) and excessive wetness (precipitation is more than enough to meet evapotranspiration demand and recharge the soil). The CMI has been adopted by the U.S. Department of Agriculture and is published in its *Weekly Weather and Crop Bulletin* as an indicator of the availability of moisture to meet short-term crop needs (Wilhite and Glantz 1985). The CMI is most effective measuring agricultural drought during the warm season (i.e., growing season).

**THE POST-PALMER ERA.** In the decades since Palmer introduced the PDSI, PHDI, and *Z* Index, several other drought indices have been developed and adopted, but none has proven superior enough to relegate Palmer's Index to the dusty annals of history. Some of these indices applied old concepts to new applications, while others addressed inadequacies in the Palmer model.

Shear and Steila (1974) and Steila (1987) proposed an approach of using water budget analysis to identify moisture anomalies. Their procedure, like Palmer's, accounts for precipitation, potential evapotranspiration, and soil moisture, but yields moisture status departure values that are expressed in the same units as precipitation; that is, they are spatially applicable water depth measures having equivalent meteorological significance in diverse climatic realms.

Keetch and Byram (1968) developed an index of drought for use by fire control managers. Based on a 203-mm (8 in.) soil moisture storage capacity, the Drought Index (DI) is expressed in hundredths of an inch of soil moisture depletion, ranging from 0 (no moisture deficiency) to 800 (absolute drought). Computation of the DI is based on a daily water-budgeting procedure whereby the drought factor is balanced with precipitation and soil moisture. The Keetch–Byram Drought Index (KBDI) has become widely used in wildfire monitoring and prediction.

Much of the work in developing drought indices has focused on meteorological or agricultural applications. As noted by Dracup et al. (1980), hydrologic study of droughts in terms of duration, magnitude (average deficit), and severity (total deficit) was greatly neglected during the first half of the twentieth century, with much of the research limited to specific basins or particular historical droughts. They identified some notable exceptions, however, including Huff and Changnon (1964), who developed a method of estimating drought streamflow frequency by using low-precipitation frequency and a single geomorphic index; Whipple (1966), who applied the station–year method of regional frequency analysis to multiyear hydrologic droughts; and Yevjevich (1967), who applied the statistical theory of runs to the analysis of drought events. Yevjevich (1967) noted that continental-scale hydrologic droughts should be described by their duration, areal extent, severity (intensity), probability of recurrence, and initiation or termination (i.e., their location in time). Dracup et al. (1980) utilized long-term mean annual streamflow (which they also referred to as runoff) to develop a stochastic model for generating hydrologic drought events and performing regional drought frequency analysis. They expanded upon Yevjevich's (1967) theory of runs by defining a drought event as consisting of consecutive years for which the mean annual streamflow was below the long-term mean, and characterized each drought event with the following three attributes: duration (the number of consecutive years for which the annual streamflow is below the long-term mean), severity (the cumulative deficit of streamflow for that duration), and magnitude (the average deficit of streamflow for that duration). They used the ratio, $R/P$, where $R$ is mean annual runoff and $P$ is annual precipitation, to investigate the nonstationarity of the streamflow records, but also noted that this runoff coefficient can be viewed as a nonlinear scaling function where $R/P$ is higher than average for high-flow (or high precipitation) years and lower than average for drought (or low precipitation) years. Additional references discussing the application of runs theory to drought indices can be found in Frick et al. (1990).

The Surface Water Supply Index (SWSI), an empirical hydrologic drought index developed for Colorado in 1981, was designed to complement the PDSI by integrating snowpack, reservoir storage, streamflow, and precipitation at high elevation as a measure of surface water status (Wilhite and Glantz 1985; Doesken et al. 1991; Garen 1993). The SWSI has a similar scale, and both the SWSI and PDSI are used together to trigger Colorado's Drought Assessment and Response Plan. The SWSI has been modified and adopted by other western states and is computed primarily for river basins. While noting that the index is very useful in assessing (and predicting) the surface water supply status, Doesken et al. (1991) and Doesken and Garen (1991) expressed several concerns about the SWSI, including the following: there is a lack of consensus over the definition of surface water supply; the factor weights vary from state to state and, in some cases, from month to month, resulting in SWSIs with differing statistical properties; and 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.

The effect of changing water demand on the severity of drought was illustrated by Frick et al. (1990) in a study of the impact of prolonged droughts on the water supplies of the city of Fort Collins, Colorado. Increased population and industrial development result in a greater demand for water, which implies an increasing vulnerability of present water resource systems to the occurrence of drought, and which suggests a broader, more severe impact of drought when it does occur. Frick et al. (1990) analyzed annual streamflow data, adjusted from upstream diversions, imports, and changes in reservoir storage, and defined drought as a sustained period of low precipitation (rainfall and snow) such that the water available from the Poudre River (the water source for Fort Collins) and imported waters will not meet the needs of water users in the basin. They included a frequency analysis by determining droughts corresponding to 20-, 50-, 100-, and 500-yr return periods using modeled annual streamflow data. Fernandez and Salas (1999a) subsequently pointed out that return period techniques utilized for floods and other high-flow events may not be applicable to drought events. They suggested that representing data dependence with a simple Markov chain be utilized in analyzing runs of independent and dependent events. They illustrated their technique in a companion paper (Fernandez and Salas 1999b) by using annual precipitation, minimum streamflows, and annual streamflows as drought indices.

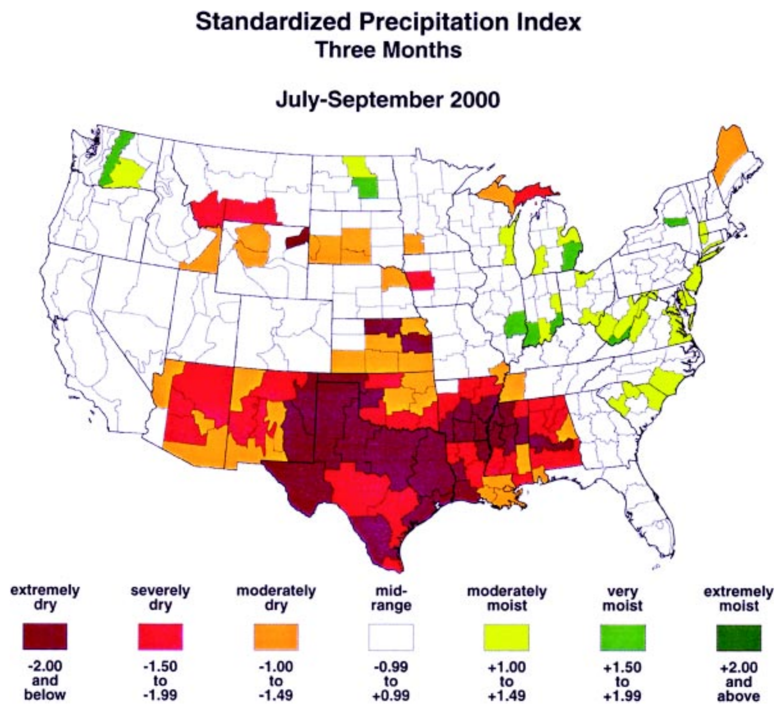


**Fig. 8. The 3-month SPI for July–Aug–Sep 2000, illustrating the extremely dry conditions that occurred during that period from the southeast and southern plains to the southwestern United States. The SPI values can be likened to a comparison of the standard deviation of precipitation from location to location.**

McKee et al. (1993) developed the Standardized Precipitation Index (SPI) as an alternative to the Palmer Index for Colorado. Historical data are used to compute the probability distribution of the monthly and seasonal (the past 2 months, 3 months, etc., up to 48 months) observed precipitation totals, and then the probabilities are normalized using the inverse normal (Gaussian) function. Guttman (1999) determined that the Pearson Type III distribution is the "best" universal model for computing the probability distribution. The SPI methodology allows expression of droughts (and wet spells) in terms of precipitation deficit, percent of normal, and probability of nonexceedance as well as the SPI (see

Fig. 7). Like the PDI, the SPI is a dimensionless index where negative values indicate drought; positive values, wet conditions. Drought intensity, magnitude, and duration can be determined, as well as the historical data-based probability of emerging from a specific drought. The different timescales (seasons) for which the index is computed address the various types of drought: the shorter seasons for agricultural and meteorological drought (see Fig. 8, cf. to the map of Palmer's *Z* Index in Fig. 4), the longer seasons for hydrological drought, etc. Although developed for use in Colorado, the SPI can be applied universally to any location.

A spectral analysis (Guttman 1997) comparing historical time series of the PDI with time series of the corresponding SPI revealed that the spectral characteristics of the PDI are spatially variant while those of the SPI are spatially invariant. The PDI spectra conform to what is expected for an autoregressive process, which is characteristic of an index with memory, while the SPI spectra conform to what is expected for a moving average process. Cross spectra between the PDI and SPI indicate that the 12-month SPI oscillations are most nearly in phase with those in the PDI. Guttman (1997) concluded that the SPI is better able to show how drought in one region compares to drought in another region.

A new drought atlas was prepared in the 1990s in a joint effort between the National Oceanic and Atmospheric Administration's (NOAA) National Climatic Data Center, the U.S. Army Corps of Engineers, the U.S. Geologic Survey, and the IBM Thomas J. Watson Research Center (Guttman et al. 1991; Willeke et al. 1994; Teqnical Services 1997). Drought was depicted in this national atlas in terms of streamflow, soil moisture (the PMDI was used as a proxy), and precipitation probabilities (Guttman et al. 1991). For durations of 1, 2, 3, 6, 12, 24, 36, and 60 months, beginning in each calendar month January–December, regional precipitation quantile values for probabilities of 0.02, 0.05, 0.10, 0.20, 0.50, 0.80, 0.90, 0.95, and 0.98 were calculated using *L*-moment methodology (Guttman 1993; Guttman et al. 1993). Data from 1119 stations from the National Climatic Data Center's U.S. Historical Climatology Network (Easterling et al. 1996) were analyzed to generate these statistics for 111 regions. The regions were identified by analyzing the "precipitation climate" of each station. The following seven variables described this precipitation climate (Guttman 1993):

1) site latitude,
2) site longitude,
3) site elevation (these first three variables describe the geographical location),
4) mean annual precipitation amount,
5) the ratio of the mean precipitation for the two consecutive months with the lowest mean amount in the year to that for the two consecutive months with the highest mean amount,
6) the beginning month of two consecutive months with the highest mean amount in the year, and
7) the beginning month of two consecutive months with the lowest mean amount in the year (these latter three variables describe the average variability of the annual cycle of precipitation).

The climatic water budget (Leathers and Robinson 1995; Leathers 1997) was utilized for operational drought monitoring in the northeastern United States. It is based on the climatic water budget methodology developed by Thornthwaite and Mather to monitor values of soil moisture surplus, soil moisture deficit, and runoff on a monthly temporal scale.

NOAA has applied satellite-based technology to the real-time monitoring of drought. The vegetation condition index (VCI), computed from satellite Advanced Very High Resolution Radiometer (AVHRR) radiance (visible and near infrared) data and adjusted for land climate, ecology, and weather conditions, showed promise when used for drought detection and tracking (Kogan 1995). The VCI utilizes the close dependence of vegetation on climate, which harks back to the principles that guided German biologist W. Köppen in his development of a vegetation-based climate classification system some 90 years earlier. The VCI allows detection of drought and (is a potentially global standard for) 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 during the summer growing season. It has limited utility during the cold season when vegetation is largely dormant.

New drought indices have been developed by researchers in other countries for applications and locales where the Palmer Index proved inadequate. Dependable rains (DR), defined as the amount of rainfall that occurs statistically in four out of every five years, have been applied by Le Houorou et al. (1993) to the African continent. The National Rainfall Index (RI), used by Gommes and Petrassi (1994) in another study of precipitation patterns in Africa, allows comparison of precipitation patterns across time and from country to country. The RI is a national-scale index, computed by weighting the national annual precipitation by the long-term averages of all of the stations

**Table 3. The Drought Monitor categories (adapted from Svoboda 2000).**

| Drought Monitor category | Description |
|---|---|
| D0 | Abnormally dry |
| D1 | Moderate drought |
| D2 | Severe drought |
| D3 | Extreme drought |
| D4 | Exceptional drought |

within the nation. The Australian Drought Watch System is based on consecutive months (at least three) with precipitation below a certain decile threshold, where the deciles are determined from the cumulative frequency of the distribution of ranked monthly and annual precipitation totals (Wilhite and Glantz 1985).

There are several extensive reference lists (Friedman 1957; Palmer and Denny 1971; World Meteorological Organization 1975a,b, 1985; Hasemeier 1977; Wilhite and Hoffman 1980; Wilhite and Wood 1983; NOAA 1989) that the reader may consult about drought and other (similar) drought indices that were not discussed in this review paper. Additional references for indices that were developed for regional studies can be found in Frick et al. (1990).

**THE DROUGHT MONITOR.** As the twentieth century drew to a close, a new drought monitoring tool was developed in a federal–state collaborative effort to consolidate and centralize drought monitoring activities. Agencies within NOAA and the U.S. Department of Agricultural (USDA) teamed with the National Drought Mitigation Center to produce a weekly Drought Monitor (DM) product that incorporates climatic data and professional input from all levels (Svoboda 2000).

Since no single definition of drought works in all circumstances (as seen above), the DM authors rely on the analyses of several key indices and ancillary indicators from different agencies to create the final map. The key parameters include the PDI, CMI, soil moisture model percentiles, daily streamflow percentiles, percent of normal precipitation, topsoil moisture (percent short and very short) generated by the USDA, and a satellite-based Vegetation Health Index [(VHI) related to the VCI mentioned earlier]. The ancillary indicators include such indices as the SWSI, the KBDI, SPI, snowpack conditions, reservoir levels, groundwater levels determined from wells, USDA-reported crop status, and direct in situ soil moisture measurements. Some of these ancillary indicators are available in a delayed mode or only on a local/regional basis.

The key parameters are objectively scaled to five DM drought categories (these categories and their labels are listed in Table 3). The classification scheme includes the categories D0 (abnormally dry area) to D4 (exceptional drought event, likened to a drought of record) and labels indicating which sectors are being impacted by drought (A for agricultural impacts, W for hydrological impacts, and F to indicate the high risk of wildfires). The DM maps are based on many objective inputs, but the final maps are adjusted manually to reflect real-world conditions as reported by numerous experts throughout the country (Svoboda 2000). Consequently, the DM is a consensus product reflecting the collective best judgement of many experts based on several indicators.

The DM draws its strength from the collaborative input at the federal (USDA, NOAA), regional (NOAA Regional Climate Centers), state, and local levels and from the objective synthesis of several drought-related indices. A limitation of the DM lies in its attempt to show drought at several temporal scales (from short-term drought to long-term drought) on one map product. The intent of the DM is not to replace any local or state information or subsequently declared drought emergencies or warnings, but rather to provide a general assessment of the current state of drought around the United States, Pacific possessions, and Puerto Rico (Svoboda 2000). The DM is currently distributed via the Internet (http://enso.unl.edu/monitor/monitor.html).

**SUMMARY AND CONCLUSIONS.** The monitoring and analysis of drought have long suffered from the lack of an adequate definition of the phenomenon due to its complex nature and widespread impacts. This has affected the development of drought indices, which have slowly evolved during the last two centuries from simplistic approaches based on some measure of rainfall deficiency, to more complex problem-specific models. These models continue to evolve as new data sources become available. The incorporation of evapotranspiration as a measure of water demand by Thornthwaite led to the landmark development by Palmer of a water-budget-based drought index that is still widely used 35 years later.

Any comprehensive drought index that can be applied on a national scale must address the total environmental moisture status. Palmer attempted this with his index, but he faced a dilemma in trying to keep a complicated index simple. Consequently, the Palmer Index has been criticized for how it treats factors such as potential evapotranspiration, runoff, snowmelt, and distribution of precipitation and evapotranspiration within a month or week. Soil moisture is represented using a two-layer model that addresses only moisture in the surface layers (i.e., down to the "root zone"), so the deeper groundwater processes associated with hydrologic drought are not represented in Palmer's model. The SWSI complements the Palmer Index by addressing such factors as snowpack and the deeper groundwater issue through proxies such as streamflow and reservoir storage. However, the SWSI is a regional index computed primarily for river basins in just the western states.

As the twentieth century concluded, the monitoring of drought took a slightly different approach with the establishment of the Drought Monitor. The Drought Monitor attempts to assess the total environmental moisture status by looking at all of the indicators that are available, essentially incorporating the best drought monitoring tools into one product that can be utilized by all users. Some of these indicators can be converted into a common standardized form, such as a percentile ranking, allowing them to be incorporated into an objective "blended" index (R. Tinker 2001, personal communication), but others need subjective interpretation in order to be useful.

With the Drought Monitor, considerable progress has been made in developing a comprehensive, objective national drought index that overcomes some of the deficiencies in other drought indices. Further improvement is possible, however, by incorporating additional indicators of drought impacts, including reservoir levels and groundwater (i.e., well) measurements of aquifer status, in situ measurements of soil moisture to "ground truth" modeled values, potential moisture stored in snowpack (the SNOTEL measurements of snow water equivalent in the U.S. western mountains are a good example), and some measure of the temporal distribution of precipitation (e.g., the number of consecutive dry days, or the average number of days between precipitation events, scaled to some base reference). State or regional networks exist for some of these variables, but the data are not in a form that lends itself to a national drought assessment. In order to be useful for operational drought monitoring, 1) these data need to be available on a near-real-time basis; 2) the data need to be monitored on a national scale, which will require the establishment of national networks for some variables; 3) complete and reliable historical data are needed over a common reference period to allow conversion of the observations to a meaningful form (such as a percentile ranking, which is the common practice for the Drought Monitor objective "blends") that could be merged objectively with the other indicators; and 4) the data need to be debiased to remove nonclimatic influences (such as those arising from water management practices).

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