The Palmer Drought Severity Index: Limitations and Assumptions

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ABSTRACT

The structure of the Palmer Drought Severity Index (PDSI), which is perhaps the most widely used regional index of drought, is examined. The PDSI addresses two of the most elusive properties of droughts: their intensity and their beginning and ending times. Unfortunately, the index uses rather arbitrary rules in quantifying these properties. In addition, the methodology used to standardize the values of the PDSI for different locations and months is based on very limited comparisons and is only weakly justified on physical or statistical grounds. Under certain conditions, the PDSI values are very sensitive to the criteria for ending an "established" drought and precipitation during a month can have a very large effect on the PDSI values for several previous months.

The distribution of the PDSI conditioned on the value for the previous month may often be bimodal. Thus, conventional time series models may be quite limited in their ability to capture the stochastic properties of the index.

1. Introduction

Droughts are, by nature, regional phenomena. For this reason, several indicators exist that attempt to encapsulate drought severity on a regional basis. Perhaps the best known of these is the Palmer Drought Severity Index (PDSI). Palmer (1965) defined a drought period as "an interval of time, generally of the order of months or years in duration, during which the actual moisture supply at a given place rather consistently falls short of the climatically expected or climatically appropriate moisture supply". Working from this definition, Palmer (1965) developed the PDSI as a means of measuring the severity of drought. This index has also been referred to as simply the Palmer Index, since it also evaluates wet situations. However, here interest is centered on droughts, and the index will be referred to as the PDSI.

The PDSI is widely used. For example, during the growing season values of the PDSI for climatic divisions of the United States are shown in the *Weekly Weather and Crop Bulletin*, published jointly by the U.S. Departments of Commerce and Agriculture. The index has also been used by various researchers to illustrate the areal extent and severity of drought in the northeastern United States during the early to mid-1960s (Palmer, 1967) and across the United States during the hot, dry summer of 1980 (Karl and Quayle, 1981). Felch (1978) used the PDSI to compare droughts of the 1930s, 1950s and mid-1970s across the continental United States. Lawson *et al.* (1971) studied the spatial and temporal characteristics of droughts in Nebraska using the PDSI. Dickerson and Dethier (1970) applied the PDSI for determining the frequencies of various drought severities in the northeastern United States. Eigenvector analyses of PDSI values have been made for 53 climatic divisions of the upper Midwest (Klugman, 1978) as well as for the entire United States for the years 1931–40 (Skaggs, 1975). Karl and Koscielny (1982) and Diaz (1983) used the PDSI to study the spatial and temporal characteristics of dry and wet episodes over the contiguous United States during 1895–1981. Kappel (personal communication, 1983) used PDSI maps from April 1975 to July 1976 to develop a crude relationship between areas of drought and increasing fire danger in Minnesota and Wisconsin during 1976. Puckett (1981) reconstructed a 230-year record of the PDSI for northern Virginia using a relationship with variations in the widths of tree rings.

Although referred to as an index of meteorologic drought, the method takes into account precipitation, evapotranspiration and soil moisture conditions, all of which are determinants of hydrologic drought. Fieldhouse and Palmer (1965) note that the PDSI should be related to water supplies in streams, lakes and reservoirs and hence be of interest to hydrologists as well as to meteorologists and climatologists. Bowles *et al.* (1980) used the PDSI to evaluate indices they developed for three municipal and three irrigation water supply systems in Utah.

An areal study of droughts generally requires an "objective" index of drought severity. The PDSI is one of the few general indices of drought readily available and is standardized to facilitate direct comparisons of PDSI between different regions. Hence, as referenced above, the method has been used extensively in the literature. Karl (1983) examined the sensitivity of the spatial characteristics of drought duration indicated by the PDSI to values of available water capacity and weighting factors used in the index. However, no overall examination has been made of the structure of the method. Here, the procedure for computing the Palmer Drought Severity Index will be discussed, followed by a critique of the method. The computational procedure will be described in detail, in part because it is usually (if not always) glossed over in descriptions of the method, and in part because it will help illustrate some of the deficiencies in the method which have not been well documented.

2. The computational procedure

Palmer's method begins with a water balance (usually on a monthly or weekly basis) using historic records of precipitation and temperature. Soil moisture storage is handled by dividing the soil into two layers and assuming that 25 mm of water can be stored in the surface layer. The underlying layer has an available capacity that depends on the soil characteristics of the site being considered. Moisture cannot be removed from (recharged to) the underlying layer until all of the available moisture has been removed from (replenished in) the surface layer. Potential evapotranspiration (PE) generally is computed using Thornthwaite's method (Thornthwaite, 1948). Evapotranspiration losses from the soil occur if $PE > P$, where P is precipitation for the month. Evapotranspiration loss from the surface layer L_s is assumed to take place at the potential rate. It is assumed that loss from the underlying layer L_u depends on initial moisture content in the underlying layer, potential evapotranspiration and the combined available moisture capacity (AWC) in both soil layers. That is, if $PE > P$,

$$L_s = \min[S_s, (PE - P)],$$

$$L_u = [(PE - P) - L_s]S_u/AWC, \quad L_u \leq S_u,$$

where P is the precipitation and S_s and S_u are the amounts of available moisture stored at the beginning of the month in the surface and underlying layers respectively. Runoff is assumed to occur if and only if both layers reach their combined moisture capcity AWC.

As part of the water balance, Palmer's method computes three additional terms: potential recharge, potential loss and potential runoff. Potential recharge (PR) is defined as the amount of moisture required to bring the soil to field capacity:

$$PR = AWC - (S_s + S_u). \tag{1}$$

Potential loss (PL) is defined as the amount of moisture that could be lost from the soil to evapotranspiration provided precipitation during the period was zero:

$$PL = PL_s + PL_u, \tag{2}$$

where

$$PL_s = \min(PE, S_s),$$

$$PL_u = (PE - PL_s)S_u/AWC, \quad PL_u \leq S_u.$$

Potential runoff (PRO) is defined as potential precipitation minus potential recharge. Palmer (1965) assigned potential precipitation as being equal to AWC. Thus,

$$PRO = AWC - PR = S_s + S_u. \tag{3}$$

Palmer (1965) recognized that "this is not a particularly elegant way of handling this problem" and noted that were he to redo his analyses he would redefine potential precipitation as some value such as three times the normal precipitation for the month. This would remain a fairly arbitrary approach but would at least recognize that precipitation and available water capacity are unrelated terms.

The four potential values—PE, PR, PL and PRO—are used to compute four coefficients which are dependent on the climate of the area being analyzed:

$$\alpha_j = \overline{ET}_j/\overline{PE}_j,$$

$$\beta_j = \bar{R}_j/\overline{PR}_j,$$

$$\gamma_j = \overline{RO}_j/\overline{PRO}_j,$$

$$\delta_j = \bar{L}_j/\overline{PL}_j, \quad j = 1, \ldots, 12, \tag{4}$$

where the overbars refer to the fact that the coefficients are computed using average values for month j. A separate set of coefficients is determined for each of the 12 months.

These coefficients are used to compute the differences d for each month between the actual precipitation for the month P and the "CAFEC" (Climatically Appropriate For Existing Conditions) precipitation $\hat{P}$ such that

$$\begin{aligned} d &= P - \hat{P} \\ &= P - (\alpha_j PE + \beta_j PR + \gamma_j PRO - \delta_j PL). \end{aligned} \tag{5}$$

The definition of $\hat{P}$ in Eq. (5) is analogous to a simple water balance where precipitation is equal to evapotranspiration plus runoff (and ground-water recharge) plus or minus any change in soil-moisture storage. A "moisture anomaly index" Z, is defined as

$$Z = K_j d, \tag{6}$$

where K_j is a weighting factor defined as

$$K_j = 17.67\hat{K}_j / \sum_{i=1}^{12} \bar{D}_i \times \hat{K}_i, \quad j = 1, \ldots, 12, \tag{7}$$

where $\bar{D}_j$ is the average of the absolute values of d for month j and

$$\hat{K}_j = 1.5 \log_{10}\left(\frac{T_j + 2.8}{\bar{D}_j}\right) + 0.50, \tag{8}$$

where

$$T_j = (\overline{PE}_j + \bar{R}_j + \overline{RO}_j)/(\hat{P}_j + \bar{L}_j).$$

The parameter T_j is a measure of the ratio of "moisture demand" to "moisture supply" for the month and region. The purpose of the weighting factors is to adjust the departures from normal precipitation d such that they are comparable among different areas and for different months. For example, ideally $Z = -4.0$ during July in Oklahoma is equivalent to $Z = -4.0$ during February in Virginia in terms of a moisture departure from "climatically normal conditions for the month. Weighting factor K_j tends to be large in arid regions and small in humid regions. During the derivation of K_j, Palmer (1965) assumed that the economic consequences of the driest year in one place were the same as those of the driest year in other places. The influence of large-scale changes in water usage such as those resulting from reservoir development, urbanization or changes in irrigation practices are ignored. Eqs. (7) and (8) were derived using data from nine areas of the United States. Their complexity and unusual form result from the difficulty Palmer had in deriving them.

The moisture anomaly index Z thus expresses a relative departure of the weather of a particular month and location from the average moisture conditions of that month. Palmer (1965) evaluated the accumulation of the moisture anomaly index Z for the 13 driest intervals in his two original study areas (central Iowa and western Kansas) and noted that they plotted as a straight line on a graph of accumulated Z versus length of dry period as shown in Fig. 1. He defined these dry periods as extreme drought and assigned a numerical drought severity value of PDSI = −4.0 to an "eyeball-fit" line through the 13 points of Fig. 1. He then subdivided the region between extreme drought and an accumulated Z of zero by three lines which he arbitrarily defined as the upper limits of "severe drought" (PDSI = −3.0), "moderate drought" (PDSI = −2.0) and "mild drought" (PDSI = −1.0). Palmer's complete classification of droughts is included in Table 1. Note that by reversing signs, similar definitions were developed for wet spells.

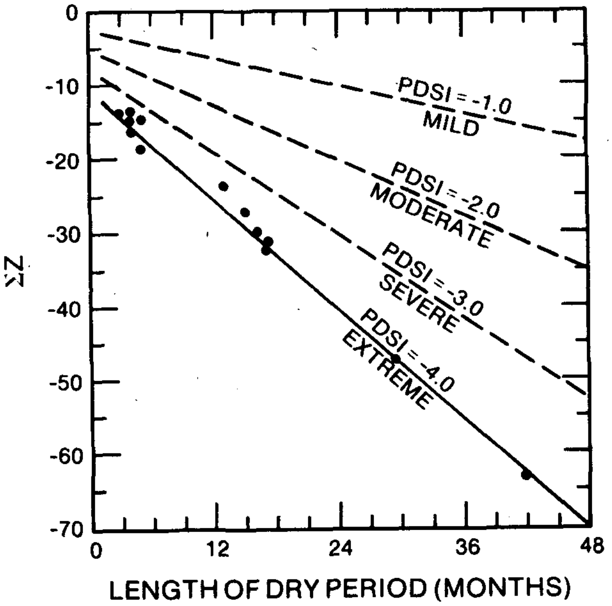

FIG. 1. Accumulated values of the moisture anomaly index Z during the driest periods of various lengths in central Iowa and western Kansas (after Palmer, 1965).

TABLE 1. Classification of recent weather according to PDSI (X).

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

Based on Fig. 1, drought severity for the ith month, $X(i)$, can be described by

$$X(i) = \sum_{t=1}^{i} Z(t)/(2.691 + 0.309i). \tag{9}$$

Note that there appears to be a slight typographical error in Eq. (9) as it is shown on page 21 of Palmer (1965). Unfortunately, Eq. (9) gives the same weight to moisture deficiencies that occurred several months ago as it does to moisture deficiencies of the most recent month. Palmer (1965) suggested that a more appropriate index would be of the form

$$X(i) = Z(i)/3 + cX(i - 1). \tag{10}$$

Note that Eqs. (9) and (10) are equivalent for the first month of a dry spell $[X(i - 1) = 0]$. Palmer (1965) determined c to be 0.897. This value of c maintains X at a given level from month to month for rates of Z accumulation that maintain a drought of constant severity in Fig. 1. Palmer's final expression for drought severity is

$$X(i) = 0.897X(i - 1) + Z(i)/3, \tag{11}$$

where $X(i)$ is the value of the PDSI for the ith month.

After a dry spell, consistently normal or wet weather will eventually result in values of X computed using

Eq. (11) approaching zero. However, Palmer (1965) found this requirement to be too stringent for the termination of a drought. In addition, application of Eq. (11) requires identification of the initial month of a dry spell. Similar conclusions were reached for wet spells. Palmer was therefore confronted with the problem of establishing the beginning and end of a drought or wet spell. His solution was to use separate bookkeepings and Eq. (11) to keep track of three indices defined as follows:

X_1 = severity index for a wet spell that is becoming "established,"
X_2 = severity index for a drought that is becoming "established,"
X_3 = severity index for any wet spell or any drought that has become "established."

The variable X_1 is restricted to nonnegative values and X_2 to nonpositive values. The values of X_1 and X_2 are set to zero when computations of Eq. (11) violate these restrictions. A drought is considered established when $X_2 \leqslant -1.00$ for the first time since a previously established drought or wet spell has ended. A wet spell is considered established when $X_1 \geqslant 1.00$ for the first time since a previously established drought or wet spell has ended. At these times, $X_3 = X_2$ for an established drought or $X_3 = X_1$ for an established wet spell. An established drought or wet spell is considered to definitely end when the index reaches the "near normal" category which lies between −0.50 and +0.50. At this point, X_3 returns to zero. The termination of an established drought is assumed to occur when $Z(i) \geqslant Z_e(i)$ where

$$Z_e(i) = -2.691X_3(i-1) - 1.5, \qquad (12)$$

where $Z_e(i)$ is the moisture required to reduce the severity of an established drought to −0.50 in a single month. Similarly, the termination of an established wet spell is assumed to occur when $Z(i) \leqslant Z_e(i)$ where, in this case,

$$Z_e(i) = -2.691X_3(i-1) + 1.5. \qquad (13)$$

Eqs. (12) and (13) are derived by solving for $Z(i)$ in Eq. (11) and substituting −0.50 and 0.50, respectively, for $X(i)$. Rather than simply using Eqs. (12) or (13) to determine whether an established drought or wet spell has ended, Palmer (1965) relies on the computation of a "percentage probability" that an established drought or wet spell has ended where

$$P_e(i) = \frac{100 \sum_{j=0}^{j*} U(i-j)}{Z_e(i) + \sum_{j=1}^{j*} U(i-j)}, \qquad (14)$$

where $0 \leqslant P_e(i) \leqslant 100$. It is important to note, as Palmer did, that P_e is not really a probability in the conventional sense but rather a measure of the ratio of moisture received to that required to end an established drought or wet spell. The definition of $U(i)$ depends on whether a drought or wet spell has been established. In the case of an established drought, Palmer (1965) notes that a value of $Z = -0.15$ will maintain an index of −0.50 from month to month. Therefore, any value of $Z \geqslant -0.15$ will tend to end a drought, and he defines $U(i)$ as

$$U(i) = Z(i) + 0.15. \qquad (15)$$

After a drought has become established ($X \leqslant -1.00$), Eq. (15) applies to the first month having $Z \geqslant -0.15$ and is computed for each successive month until the computations show a value of P_e equal to either 0 or 100. The parameter $j*$ in Eq. (14) corresponds to the number of successive values of $U(i)$ computed immediately prior to the current month. Similar computations are performed to evaluate P_e for an established wet spell except in this case

$$U(i) = Z(i) - 0.15.$$

There is an inconsistency in the use of Eq. (14) to indicate the end of a drought or wet spell. This occurs because Eq. (14) may indicate that a drought has ended $[P_e(i) = 100]$ even though $Z(i) < Z_e(i)$. To illustrate this inconsistency, first note that $P_e(i)$ in Eq. (14) will equal or exceed 100 whenever

$$U(i) \geqslant Z_e(i). \qquad (16)$$

Substituting Eq. (15) into (16) yields

$$Z(i) \geqslant Z_e(i) - 0.15,$$

as the criterion resulting from Eq. (14) for ending an established drought, rather than $Z(i) \geqslant Z_e(i)$. Likewise, Eq. (14) may indicate an established wet spell has ended even though $Z(i) > Z_e(i)$.

The drought index X for a particular month is set equal to X_1, X_2, or X_3. Often only one of these three indices is nonzero, and X is set to the nonzero index. However, many conflicting cases can arise and the appropriate index to use for X is not always obvious. For example, it is common for both wet spells ($X_1 > 0$) and dry spells ($X_2 < 0$) to be simultaneously indicated as becoming established. It is also common for a situation such as $X_1 \geqslant 1.00$ and $X_3 \leqslant -1.00$ to occur simultaneously.

In order to select the appropriate value of X when the choice of index is not obvious, Palmer devised a set of operating rules that rely heavily on computing values of X_1, X_2 and X_3 over several months and then backtracking based on the direction in which the weather appeared to be going. An example of the selection procedure is shown in Table 2. First, observe how the values of X_3 were assigned. The negative values of X_3 indicate that an "established drought" occurred for December 1931–October 1932. Eq. (11)

TABLE 2. Palmer Drought Severity Index for Washington, DC, December 1931–December 1932.

Month	Z	P_e	X_1	X_2	X_3	X	X^{*a}
December	−2.75	0.0	0.0	0.0	$\underline{-4.75}^b$	−4.75	−4.75
January	0.36	4.5	$\underline{0.12}$	0.0	−4.14	0.12	−4.14
February	−0.51	1.5	0.0	$\underline{-0.17}$	−3.88	−0.17	−3.88
March	3.83	45.4	$\underline{1.28}$	0.0	−2.20	1.28	−2.20
April	−0.89	39.6	$\underline{0.85}$	−0.30	−2.27	0.85	−2.27
May	1.15	58.6	$\underline{1.15}$	0.0	−1.66	1.15	−1.66
June	−0.34	58.9	0.91	$\underline{-0.11}$	−1.60	−0.11	−1.60
July	−1.41	44.5	0.35	$\underline{-0.57}$	−1.90	−0.57	−1.90
August	−2.89	7.5	0.0	$\underline{-1.47}$	−2.67	−1.47	
September	0.05	11.5	$\underline{0.02}$	−1.30	−2.38	0.02	
October	4.12	88.9	$\underline{1.39}$	0.0	−0.76	1.39	
November	4.08	100.	$\underline{2.61}$	0.0	$\underline{2.61}$	2.61	
December	1.88	0.0	0.0	0.0	$\underline{2.97}$	2.97	

[a] Values for X if $P_e = 0.0$ for August.

[b] Values of X_1, X_2 and X_3 chosen for X are underlined.

was used recursively to compute these values. Then, in November, the large value of $Z = 4.08$ resulted in $P_e = 100$, i.e., a definite end to the established drought. Because $X_1 \geqslant 1.00$, November also marked the beginning of an established wet spell which continued in December. Now observe how the values of X were assigned. Since X_3 for December 1931 was negative and $P_e = 0.0$, X was set equal to X_3. However, $0 \leqslant P_e < 100$ in January and the method did not originally assign $X = X_3$. Values for X were not assigned until P_e reached 100 in November at which point $X = X_3 = X_1 = 2.61$. The method then backtracked from November through January using the following rules:

(i) assign $X = X_1$ until $X_1 = 0$;
(ii) then assign $X = X_2$ until $X_2 = 0$;
(iii) repeat steps (i) and (ii) until a month was reached which already had an X value assigned, i.e., December 1931.

If P_e returns to zero during an established drought or wet spell, then $X = X_3$ for all values of X between and including the months during which $P_e = 0.0$. For example, X^* shows the values of X for December–July if P_e for August 1932 had been zero. The values of X^* differ substantially from those of X. The value of PDSI for January changes from "near normal" to "extreme drought" and the PDSI for March from "slightly wet" to "moderate drought."

Whenever a drought or wet spell has become "established" and $0 < P_e < 100$, a value for the PDSI can not be assigned until P_e reaches 0 or 100. This obviously causes problems when the PDSI is used in an operational mode (calculated in real time). Values in the *Weekly Weather and Crop Bulletin* circumvent this problem, by letting $X = X_3$ whenever $0 < P_e \leqslant 50$ and letting either $X = X_1$ or $X = X_2$, whichever results in an index having the opposite sign of X_3, whenever $50 < P_e < 100$ (T. Heddinghaus, personal communication, 1983). Other backtracking problems are resolved by selecting the PDSI as X_1 or X_2, whichever has the largest absolute value, whenever X_3 equals zero.

3. A critique

Felch (1978) notes that there are people who oppose development of a drought index on the grounds that the problem is much too complex to take full account of all the pertinent physical and biological factors. It is not the purpose of this paper to address this issue. The PDSI is probably the most widely used drought index and therefore an understanding of its properties and assumptions is important.

From the preceding description it should be evident that computations of the PDSI are quite involved. A number of arbitrary assumptions were required during development of the method, and it uses several unfamiliar terms and definitions.

The backbone of the method is a water balance computation. There are several limitations involved in using water balance models (Alley, 1984). The first is that there is no universally accepted method of computing potential evapotranspiration. The method of Thornthwaite (1948) has typically been used; however, other applicable methods could be employed. The water balance model assumes that the capacities of the two soil layers are independent of seasonal or annual changes in vegetation cover and root development. These temporal changes are particularly important in cultivated areas.

Most water balance models assume that evapotranspiration for a period is equal to the potential evapotranspiration whenever $P \geqslant PE$. However, precipitation and evapotranspiration often are distributed within a month or week in such a way that both periods of deficiency and surplus can occur. Particularly in late summer, simulated soil moisture at the beginning and end of the month may be very low. Yet, if $P \geqslant PE$, the model erroneously assumes evapotranspiration occurs at the potential rate for the entire month.

When $P < PE$ and soil-moisture deficits develop, almost all water balance models invoke some limitation on evapotranspiration as a function of soil-moisture content. The availability of soil moisture for plant growth over the range from field capacity to permanent-wilting point has been treated by a wide range of techniques. At one end of the spectrum, Veihmeyer and Hendrickson (1955) suggested that, in some cases, evapotranspiration may proceed at the potential rate until soil moisture approaches the permanent-wilting point. On the other hand, Thornthwaite and Mather (1955) assume the ratio of actual to potential evapotranspiration is a linear function of the ratio of available soil moisture to the available water capacity. The true relationship between actual and potential evapotranspiration will vary with rooting characteristics, soil texture and plant physiology, as well as the rate of evapotranspiration itself and climatological conditions. In the absence of a generally applicable physical model, several compromises have been made between the above two models. Most of these assume that evapotranspiration occurs at close to the potential rate until some proportion of the available water is depleted, after which the actual evapotranspiration rate is less than the potential rate. Palmer's approach is one of these compromises.

The universal designation of 25 mm as the moisture capacity of the surface layer from which evapotranspiration takes place at the potential rate seems rather arbitrary, although others have also made this assumption (see Haan, 1972). Palmer's model uses an analog of the linear approach of Thornthwaite and Mather (1955) to estimate evapotranspiration from the underlying layer. Another approach is to simply assume evapotranspiration losses from the underlying layer are equal to some percentage (often on the order of 10%) of the potential loss (for example, see Calder *et al.*, 1983; Rushton and Ward, 1979). The 25 mm moisture capacity of the surface layer is small compared to monthly values of $(PE - P)$, often observed in many climates, and the simulated soil-moisture storage in the upper layer often goes from full to empty in a single month. The assumed moisture capacity of the underlying layer is often much greater than 25 mm and, thus, after moisture is completely withdrawn from the surface layer the simulated rate of evapotranspiration will often be close to the potential rate. For these reasons, the water balance computations often are insensitive to the inclusion of the surface layer.

Perhaps the most serious deficiencies in the water balance computations are related to the estimation of runoff. Apparently Palmer's runoff term includes both recharge to ground water and overland runoff. No lag is incorporated in the Palmer model to account for the delay between generation of excess water and its appearance as runoff. In particular applications Thornthwaite and Mather (1955) and Mather (1981) suggest that, when using water balance models, approximately 50–75% of the "runoff" should be delayed each month in order to reproduce monthly flow volumes observed in streams. Of course, the fraction held back should vary with the depth and texture of the soil, physiography, size of the basin and nature of the ground-water system.

The Palmer model is a "threshold-type" model in that it assumes that runoff does not occur until the soil-moisture capacity of the upper and lower layers is filled. The limitations of this assumption have been recently reviewed by Morton (1983). Rushton and Ward (1979) found that monthly water balances lead to recharge (runoff) values which are up to 25% less than those from daily water balances, and that threshold-type models tend to underestimate recharge (runoff) during the summer and early autumn. This suggests some inconsistency in performing the PDSI computations using the same parameters for both weekly and monthly computations. The temporal aggregation of precipitation over a month (week) and the simplified treatment of runoff result in end-of-month (week) soil-moisture storage simulated by the Palmer model being more often than not at its capacity AWC for many regions. This is an unrealistic approximation. This limitation may be more important for those studies that rely heavily on a given PDSI for a specific month during a given year.

Although the PDSI is often reported for all parts of the United States and has been used on a nationwide basis and in the northern parts of the United States to examine temporal and spatial patterns of drought (e.g., see Dickerson and Dethier, 1970; Skaggs, 1975; Klugman, 1978; Karl and Koscielny, 1982), the method makes no allowance for the effect of snowmelt or frozen ground. Thus, it may provide misleading results in the northern or mountainous parts of the United States.

Although one should be aware of the limitations of the water balance model used in determining the PDSI, there are other features of the method which are perhaps more troublesome. Perhaps the most serious potential problem with the PDSI is the arbitrary designation of drought severity classes. An index value of −4.0 was defined as equivalent to extreme drought in the derivation of Eq. (11). Palmer (1965) then arbitrarily designated −3.0 as the upper limit of severe drought, −2.0 as the upper limit of moderate drought, and −1.0 as the upper limit of mild drought. It should be noted that Eq. (11) was derived using records from only central Iowa and Kansas.

In applying his method to long records in western Kansas, central Iowa and northwestern North Dakota, Palmer found that from 11 to 16% of the months were classified as severe or extreme drought and 32 to 42% of the months were classified as mild drought or drier. Fieldhouse and Palmer (1965) reported monthly values of PDSI for 1929–63 for 58 climatic divisions in the northeast United States. Approximately half of the months were classified as incipient to extreme drought ($X \leqslant -0.50$), with about 18% of the months classified as moderate to extreme drought. These results suggest that terms such as "severe" and "extreme" may be rather loosely defined by the PDSI. In any event, care should be used when referring to the drought severity classes.

Palmer attempted the difficult task of creating a drought index that is comparable between different months and different regions. An attempt was made to create a physically-based weighting factor as evidenced by the fact that T_j is the ratio of average moisture demand to average moisture supply for month j. However, Eqs. (7) and (8) are based on results from only nine climatic divisions. They were derived largely using data aggregated on the annual level; thus, their use to adjust the monthly values may not yield the desired result of comparability of the index values between months. Essentially, Eq. (8) was derived in an attempt to produce PDSI values corresponding to extreme drought ($X = -4.0$) for the driest 12-month interval in each of the nine climatic divisions. The adjustment to $\hat{K}_j$ reflected in Eq. (7) was then made such that the average annual sum of the weighted average departures ($\Sigma\bar{D}_i \times \hat{K}_i$) was the same for all nine climatic divisions. The adjustments do not provide much assurance that comparability of the PDSI exists among different regions over the range of values which the PDSI can take on. Sensitivity analyses by Karl (1983) suggest that the magnitudes of individual PDSIs are very sensitive to K_j, but overall the durations of droughts of various magnitudes are relatively insensitive.

An alternate approach would have been to simply rank the PDSI values obtained during the base period for a particular month. For example, the PDSI for January 1954 would be ranked with all other Januarys during the base period, assigning a rank of one to the lowest value, two to the second lowest, etc. The PDSI computations can then be carried out for the period of interest and the PDSI values converted to an equivalent rank (through interpolation, if necessary) during the base period. This rank would be the drought index. This would avoid the use of K_j and would provide an index of drought severity without arbitrarily defining classes such as "extreme drought." Occasionally, a value of PDSI would be outside the range of values for that month of the year computed during the base period, and it will be difficult to assign a rank. Extension of the base period to the present time would eliminate this problem. This approach, without the extended base period, can be applied to the PDSIs as currently calculated.

As illustrated in Table 2, values of the PDSI can change abruptly from one month to the next. It is not unlikely for the method to indicate a month of "moderate to extreme drought" ($X \leqslant -2.0$) followed by a month of "wet" conditions ($X \geqslant 1.0$). This is not unrealistic and the method would be fallacious if this never occurred. However, the effect on the PDSI values of precipitation that occur several months later, and the somewhat arbitrary rules which control these effects, are disturbing.

Large transitions in the drought index result from the transition values of −1.0, −0.5, 0.5 and 1.0. These transition values were chosen by Palmer (1965) somewhat arbitrarily. A drought or wet spell is assumed to be established and the computations of X_3 begin when $X_2 \leqslant -1.0$ or $X_1 \geqslant 1.0$, so long as another drought or wet spell is not already established. At this point $P_e = 0.0$. A drought or wet spell is assumed no longer to be established, and the computations of X_3 end when $X_3 \geqslant -0.5$ or $X_3 \leqslant 0.5$. At this point $P_e = 100$ (although as previously noted there is a slight discrepancy between P_e and the −0.5 or 0.5 transition values). Here the −1.0 and 1.0 transition values are referred to as the "beginning values" and the −0.50 and 0.50 transition values are referred to as the "ending values."

The number of months of PDSI values in different drought severity classes during 1931–80 is shown in Table 3 for climatic division 2 of New Jersey. This division was selected randomly for illustrative purposes, but it is a climatic division for which water balance models have often been applied and developed. Results for PDSI values based on different beginning and ending values are also shown. The beginning values have little influence on the simulated values of PDSI. For example, halving the beginning values to $X_2 \leqslant -0.5$ and $X_1 \geqslant 0.5$ resulted in values of PDSI that were the same for most months, and approximately the same number of months were contained in different drought severity classes.

The transition values indicating an end to an established drought or wet spell (ending values) have a larger influence on the PDSI. For example, a relatively large change in the number of months in various drought severity classes results from simply changing the ending values to $X_3 \geqslant -0.40$ and $X_3 \leqslant 0.40$. As illustrated earlier in Table 2, the ending criteria control the timing and occurrence of abrupt changes in the PDSI. For example, the PDSI values during 1946–50 are shown in Fig. 2 along with the values that would be obtained if the ending criterion was 0.40 rather than 0.50. There were two short periods for which the revised program resulted in later transitions from an established drought and very different values of PDSI. After several months, the revised program returned to PDSI values that were the same as the original version. Similar results were obtained in sensitivity analyses of other climatic divisions in New Jersey and Nebraska.

The occasional abrupt transitions of the PDSI values affect the development of stochastic models of the index. Time series models have been fit to PDSI

TABLE 3. Sensitivity of occurrence of drought to some assumptions of the PDSI.

PDSI modification	Number of months of PDSI in given range 1931–80 −1.99 to −1.00 (mild drought)	−2.99 to −2.00 (moderate drought)	−3.99 to −3.00 (severe drought)	$\leqslant -4.00$ (extreme drought)
None	87	67	17	20
Drought or wet spell established when $X_2 \leqslant -0.50$ or $X_1 \geqslant 0.50$ respectively	84	68	17	20
Established drought or wet spell ends when $X_3 \geqslant -0.40$ or $X_3 \leqslant 0.40$ respectively	95	76	19	19
Base period is 1951–80	93	52	15	10

values by Havens *et al.* (1968), Davis and Rappaport (1974) and Katz and Skaggs (1981). The latter examined autoregressive-moving average (ARMA) models of various orders for 344 climatic divisions and found that, based on the Bayesian Information Criterion of Schwarz (1978), an AR(1) model was preferred for about 90% of the divisions. Eq. (11) suggests that an AR(1) model might be appropriate. However, the switching among X_1, X_2 and X_3 as the value of PDSI may cause problems in the ARMA representation of a PDSI time series. In particular, for an established drought with $X(i) = X_3(i)$, the PDSI for the following month, $X(i + 1)$, may be either $X_3(i + 1)$ or $X_1(i + 1)$. If set to $X_3(i + 1)$, then $X(i + 1)$ will be computed using $X_3(i)$ in Eq. (11) and will probably not deviate much from $X(i)$. On the other hand, if set to $X_1(i + 1)$, then $X(i + 1)$ will be positive and will be much different from $X(i)$. Similar results occur for established wet spells. The result is that the conditional distribution of $X(i + 1)$ given $X(i)$ tends to be bimodal during periods of "established" droughts or wet spells. This is illustrated in Fig. 3 for various ranges of $X(i)$. The tendency for a bimodal conditional distribution for $X(i + 1)$ given $X(i)$ may cause problems in representing a PDSI time series as an ARMA process or in using PDSI as a predictor variable for streamflow. Karl (1983) also notes that only PDSIs computed on an operational basis should be used in studies attempting to demonstrate forecast skill, because the selection of X_1, X_2 or X_3 as X for the regular PDSI is often based on events occurring in subsequent months.

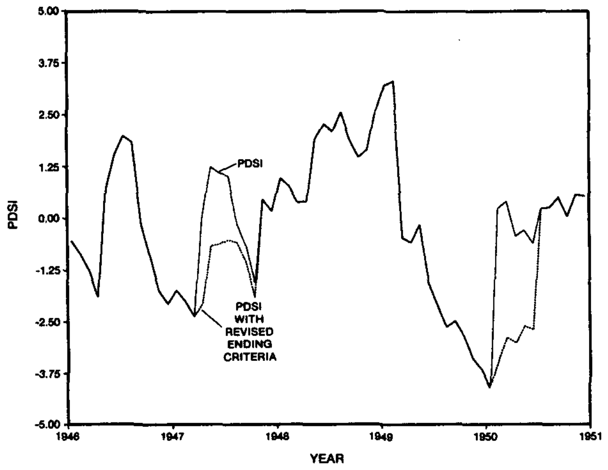

FIG. 2. Effect on PDSI values of changing ending criteria for established drought from $X_3 \geqslant -0.50$ to $X_3 \geqslant -0.40$ (1946–51 for climatic division 2 of New Jersey).

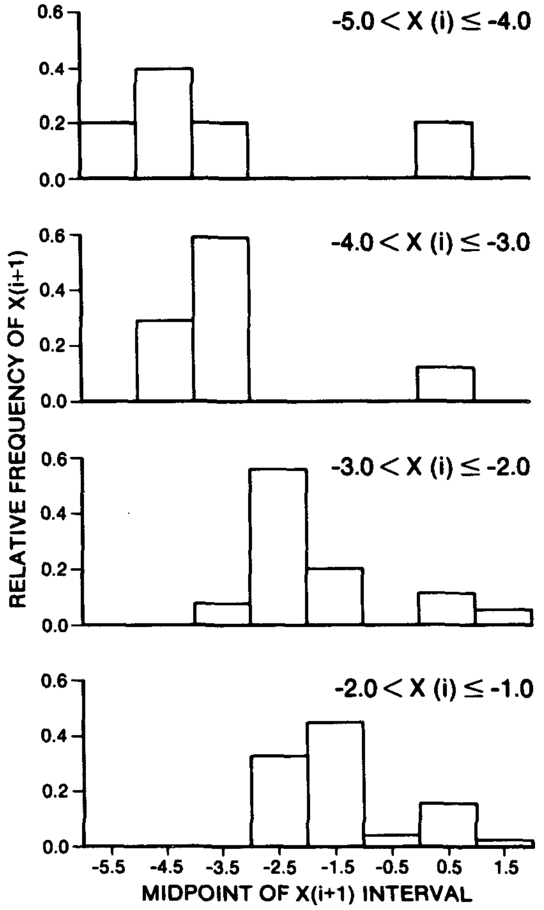

FIG. 3. Histogram of relative frequency of the PDSI for the $(i + 1)$st month, $X(i + 1)$, conditioned on four different intervals of $X(i)$ (New Jersey climatic division 2).

The Palmer method was developed and, to the author's knowledge, is often applied using the base period 1931–60 to estimate the weighting factors and parameters of Eq. (5). The effect of using the period 1951–80 as the base period is shown in Table 3. Fewer months are designated as moderate to extreme drought when using this more recent period as the base period, probably because the years 1951–80 contain the critical drought period of this century for New Jersey: the early to mid-1960s. There is some rationale for using either the more recent 1951–80 period or a longer period such as 1931–80 as the base period. The results of Table 3 suggest that there could be fairly large differences in results.

4. Ramifications for drought indices based on water balances

Regional drought indices on the scale of climatic divisions or states can be useful for several purposes. One of these is to provide decision makers with an overview of the relative degrees of abnormality of recent weather throughout the United States. A second and related purpose is to place current conditions in historical perspective. Karl and Quayle (1981) provide an example of this application using the PDSI. As another example, if reservoir storages in an area become very low, and yet the relevant drought index indicates only moderate drought, then this suggests that the present supply system is very vulnerable to drought. Regional drought indices may also have limited usefulness for forecasting variables such as short-term forecasts of irrigation requirements and longer term forecasts of crop production. Finally, these indices may be useful for characterizing the spatial and temporal features of historical dry episodes over large regions. Karl and Koscielny (1982) and Diaz (1983) provide examples of this application using the PDSI.

The PDSI is an attempt to use a simple water balance model as the basis for developing a regional drought severity index. In developing his drought index, Palmer was confronted with a need to provide appropriate weighting of antecedent conditions with current conditions and to provide rules for determining the beginning and end of "established" droughts. These issues are not trivial. For example, in a compendium on North American droughts, Rosenberg (1978) notes that "fully half of the contributors complained that drought is a non-event and bemoan the fact that, because of this peculiar characteristic of drought, it is difficult to know when to take action and what action to take."

Palmer (1965) describes his index as a meteorological drought index but makes a number of references to agricultural and hydrologic drought. His index is not related to specific impacts of droughts. Unfortunately, it is difficult to separate factors such as beginning and end of droughts, appropriate weighting of antecedent conditions and drought severity from specific impacts and their economic consequences. Future development of drought indices should begin with a clear definition of the nature and type of drought to which the index is addressed. The question then arises, "Are water balance models an appropriate vehicle for developing such drought indices?"

There are advantages of drought indices based on simple water balance models. They can be applied throughout the United States (with perhaps some modifications for snow and/or frozen ground), and they consider both precipitation and temperature and their combined influences on evapotranspiration, soil moisture and runoff.

On the other hand, there are inherent disadvantages based on the water balance model's simplistic representation of hydrologic phenomena, especially runoff. The simulation of runoff by a water balance model is very crude, and it is difficult to account for the lag between moisture surplus and streamflow. An alternative source of information on surface runoff conditions are index streamflow-gaging stations which are used in the monthly publication *National Water Conditions* (U.S. Geological Survey, 1984). These stations have relatively long periods of record and represent relatively natural conditions. Drought indices could be developed that rely on the flows themselves or on a suitable transformation to account for a specified level of development.

Direct measurements of other variables including soil moisture and evapotranspiration are more problematic. These are areas for which water balance models may be useful in developing indices of drought. For example, Thomas *et al.* (1983) suggest that the impact of a succession of dry years on basin biota can be assessed more accurately by deviations from norms of evaporation and residual moisture than by deviations from mean annual rainfall or runoff. However, extreme caution should be exercised in using water balance variables such as soil moisture and evapotranspiration in developing indices of drought. These variables may or may not be properly simulated by a water balance model. For example, for many regions the end-of-month (week) soil-moisture storage may be unrealistically simulated by the Palmer model as more often than not at its capacity, AWC. This is an unrealistic approximation.

More information is needed on the relationship between variables simulated by water balance models and actual physical conditions and economic consequences. Without this information it is difficult to derive drought indices not based on relatively arbitrary operating rules. In the meantime, studies of the spatial and temporal characteristics of drought which use indices based in part on a water balance model should include sensitivity analysis to test the robustness of their conclusions to somewhat arbitrary assumptions used in the development of the index.

5. Summary and conclusions

The PDSI addresses two of the most elusive properties of droughts: their intensity and beginning and ending times. Unfortunately, the index uses rather arbitrary rules in quantifying these properties. In addition, the methodology used to normalize the values of the PDSI is based on very limited comparisons and is only weakly justified on a physical or statistical basis. Under certain conditions, the PDSI values are very sensitive to the criteria for ending an "established" drought. In addition, precipitation during a month can have a large effect on the PDSI values for several previous months. The conditional distribution of the PDSI given the value for the previous month may often be bimodal. Thus, conventional time series models may be quite limited in their ability to capture the stochastic properties of the index.

Published values of the PDSI are widely used, and there are likely many users who have a good engineering or intuitive judgment of their meaning. Considerable human judgment and experience, which are hard to quantify, went into development of the index. Until a "better" index is developed, the PDSI will likely continue to be used widely. This paper has documented several limitations of the method. However, more importantly, it should indicate a great need for additional research into drought indices while warning about some of the difficulties involved in their development.

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