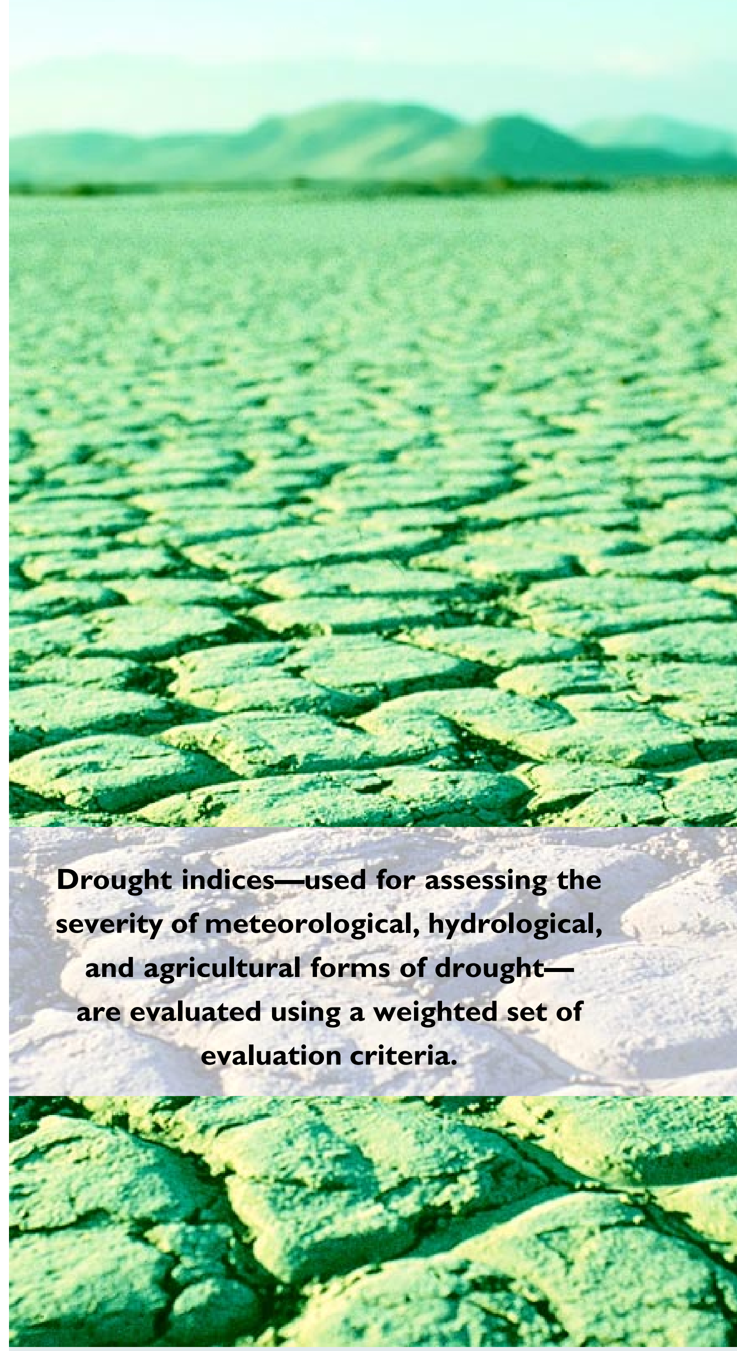
The Quantification of Drought: An Evaluation of Drought Indices

BY JOHN KEYANTASH AND JOHN A. DRACUP



Drought indices—used for assessing the severity of meteorological, hydrological, and agricultural forms of drought—are evaluated using a weighted set of evaluation criteria.

Droughts are the world's costliest natural disasters, causing an average \$6–\$8 billion in global damages annually and collectively affecting more people than any other form of natural disaster (Wilhite 2000). Given the consequences and pervasiveness of drought, it is important to assess drought severity, but the precise quantification of drought is a difficult geophysical endeavor. Numerous specialized indices have been proposed to do this; for an extensive listing of available indices, the reader is referred to WMO (1975) and Heim (2000).

The purpose of this paper is to evaluate the most prominent indices for each form of drought by applying a weighted set of six evaluation criteria. Ultimately, the drought indices are ranked in terms of usefulness for the assessment of drought severity. We are not trying to cogently define drought here; much scientific discussion has been devoted elsewhere to this topic (e.g., Dracup et al. 1980; Wilhite 2000; Wilhite and Glantz 1985).

We selected two test regions for drought index comparison: the (National Climatic Data Center) NCDC-designated Willamette Valley and North Central climate divisions of Oregon, shown in Fig. 1. They were chosen based on their distinct precipitation regimes, the presence of large rivers, and widespread agricultural activities, which make both divisions suitable for the examination of multiple drought types.

The Willamete Valley is moist, experiences mild winters, and receives consistent winter precipitation due to the westerly flow of Pacific storms. Summers are dry but relatively cool, providing the region with a Köppen climatic classification of Csb (e.g., Ahrens 1994). The primary geographic feature is the Cascade Range, which impedes the flow of Pacific air and accentuates orographic precipitation on the western

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mountain slopes. The Willamette Valley is drained by the Willamette River, the second largest river in the state. The river's headwaters are in the central Oregon Cascades, and its flow depends on snowmelt. The Willamette Valley is the most productive agricultural region in Oregon, growing more than 200 identified crops (second in diversity only to California). In particular, the region is the nation's dominant producer of grass seed, Christmas trees, blackberries, and hazelnuts (Korn 2001).

The North Central zone experiences moist winters and long, dry summers. The region is in the rain shadow of the Cascades, so divisionally averaged annual precipitation for 1961–90 is 38 cm, compared to 132 cm in the Willamette Valley [the Western Regional Climate Center (WRCC) 2001]. The Columbia River forms the northern border of the region. The Columbia River Gorge, which bisects the Cascades, is an inlet for western marine air, which helps to moderate annual temperatures. Nonetheless, hot summers lead to the Köppen classification of Csa (e.g., Ahrens 1994). Agriculturally, the North Central region is important for the production of wheat and tree fruit, notably pears, cherries, and apples.

The desire to have a common comparison period for the two divisions, across the suite of indices examined, has constrained the analysis to a 24-yr interval, water years 1976–99, where a water year is 1 October–30 September. Use of only two climate divisions provides a brief means to explore general drought index properties. Obviously, drought indices that perform inconsistently among these two regions will have limited broad applicability. Indices that perform well in both divisions have a higher likelihood of meaningful usage elsewhere, but this behavior is not guaranteed. This paper is not intended to

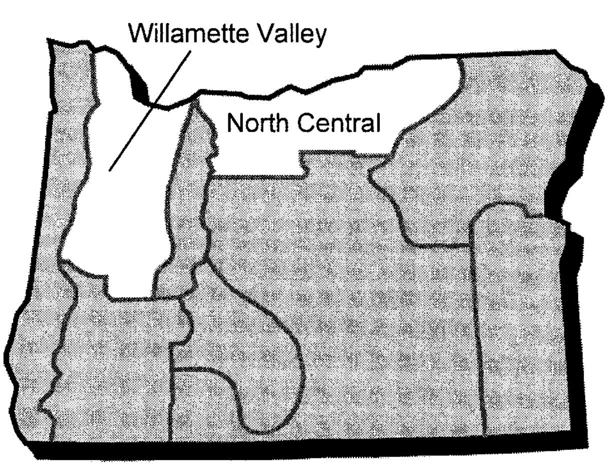


Fig. 1. The Willamette Valley and North Central climate divisions of Oregon (NCDC 2001).

dictate universal utility, so the specific application of its findings to other national climate divisions should be pursued with reserve.

Conventional scientific literature recognizes four types of drought: meteorological, hydrological, agricultural, and socioeconomic (Rasmussen et al. 1993; Wilhite and Glantz 1985). The latter form may be considered a consequence of the other drought types; unless societal demand consistently exceeds natural supply, a socioeconomic drought will not occur without one or more of the other droughts. Furthermore, the index of socioeconomic drought is clearly monetary. Consequently, this paper will only consider the physically based forms of drought.

The three physical drought types are associated with a deficiency in a characteristic hydrological variable. Meteorological drought results from a shortage of precipitation, while hydrological drought describes a deficiency in the volume of the water supply, which includes streamflow, reservoir storage, and/or groundwater heights (Wilhite 2000). Agricultural drought relates to a shortage of available water for plant growth, and is assessed as insufficient soil moisture to replace evapotranspirative losses [the World Meteorological Organization (WMO) 1975].

EVALUATION CRITERIA. Given three physical forms of drought, it is clear that there is not a single unifying technique to quantify drought severity. Even within an individual category, the supremacy of a specific index is not immediately clear. In judging the overall utility of the indices, we constructed a set of six weighted decision criteria and assigned values (1–5, 5 being the highest) to each of the evaluated indices. The criteria were established based on desirable properties that an index should ideally possess (e.g., Redmond 1991): robustness, tractability, transparency, sophistication, extendability, and dimensionality. Arguably, the list may be condensed or expanded, but we believe these six criteria provide a reasonable framework for the evaluation of drought indices without excessive complication. The rationale of each evaluation criterion follows.

Robustness. Robustness implies usefulness over a wide range of physical conditions. Robustness should be distinguished from accuracy, as the latter implies that we have some standard with which to compare our calculated severity. Furthermore, robustness considers some measure of variability of the index. Ideally, we seek an index of drought that is responsive but not temperamental. Robustness is important, but does not entirely monopolize index considerations. For example, percent of normal is not particularly robust yet is common for other reasons, such as tractability.

Tractability. Tractability represents the practical aspects of the drought index. For example, an intractable index may require high-level numerical computing, or the actual steps of the computation might be particularly complicated. An intractable index could also require data that are sparsely observed, or need an extensive historical database for its computation.

Transparency. Transparency considers the clarity of the objective and rationale behind the drought index. We think this is an important measure, as a pragmatic index of drought should be understandable not only by the scientific community but also by the affected public. Indeed, this is why water shortages are commonly described in the media using percent of normal; although crude, it is highly transparent. Hence, transparency may represent general utility.

Sophistication. Sophistication is somewhat at odds with transparency, but has been included because of the conceptual merits of an approach. A drought measurement technique may not be transparent, but it may be sophisticated and appreciable from the proper perspective. Einstein's theory of special relativity, for example, is neither transparent nor tractable, but it is certainly the superior perspective for comprehending physical motion. The level of sophistication incorporated in a drought index must also be supported by the quality of the available data and the fundamental accuracy of the assessment method.

Extendability. Extendability could be interpreted as a facet of tractability, but we separate it here for distinction. Extendability is the degree to which the index may be extended across time to alternate drought scenarios. For instance, if an index relies upon basic measured data (e.g., temperature or precipitation), then it may be constructed for long historical periods. A drought index relying upon satellite radiometric measurements, however, is only useful for the last few decades. Extendability also considers the extent that related approaches, stemming from a primary index, can also be used to further refine drought assessments in conjunction with the parent index. Redmond (1991) addressed the value of indices that consist of such subindices.

Dimensionality. Dimensionality could probably be a constituent of transparency, but we delineate it separately as it may be readily discerned. This criterion refers to the connection of the index with the physical world. It is advantageous if an index comprises fundamental units (L, M, or T), or at least is a ratio computed from physical units (e.g., percent of annual streamflow), as opposed to possessing strictly dimensionless qualities. Simple units are also desirable.

Dimensionless, normalized, and/or probabilistic renditions of indices—such as standardized anomalies or percentiles—are useful for comparing features between different locations and/or periods. The dimensionality criterion strictly considers the index itself, not subsequent data treatments.

The criteria weights—to reflect the relative importances of the evaluation criteria—are difficult to precisely justify, as their determination is ultimately affected by professional experience and personal judgment. Of course, readers are free to modify the weights to suit their own perspectives. As detailed in Table 1, we felt robustness is most important in reliably identifying drought, followed predominantly by tractability, transparency, and sophistication. Following is a discussion of selected meteorological, hydrological, and agricultural drought indices, and how their intrinsic properties relate to the evaluation criteria.

METEOROLOGICAL DROUGHT INDICES.

Discrete and cumulative precipitation anomalies. The precipitation anomaly directly measures the shortage of rainfall, and is the difference between the observation and the long-term climatological mean. This anomaly is a primitive index of drought, and is not especially informative, since the importance of the anomaly depends on climate; a monthly deficit of 1 cm is substantially more significant for a desert ecosystem compared to a montane forest.

Table 1. Weights assigned to drought index evaluation criteria.

Criterion	Wt	Relative importance
Robustness	8	28%
Tractability	6	21%
Transparency	5	17%
Sophistication	5	17%
Extendability	3	10%
Dimensionality	2	7%
Score for each criterion	1–5	
Max weighted score possible	145	

Alternatively, it is possible to consider a cumulative precipitation anomaly. Foley (1957) explicitly introduced such a technique that tallies the deviations of monthly measurements from long-term monthly averages. This clearly depicts the aggregate amount and duration of water surplus or deficit, but like the discrete precipitation anomaly, the relative importance of the cumulative precipitation anomaly depends upon the magnitude of the anomaly in relation to normal conditions. To account for this effect, Foley's approach normalizes each anomaly with respect to the annual average rainfall, with the cumulative anomaly being expressed in thousandths of the annual precipitation.

Unfortunately, the simplicity of the precipitation anomaly concept accounts for two of its weaknesses. First, the instant at which a drought begins is critical for the computation of the cumulative anomaly, but the method does not explicitly address this feature. Instead, a drought initiation time is usually identified as the point when the cumulative anomaly begins a substantial decline, which is determined subjectively.

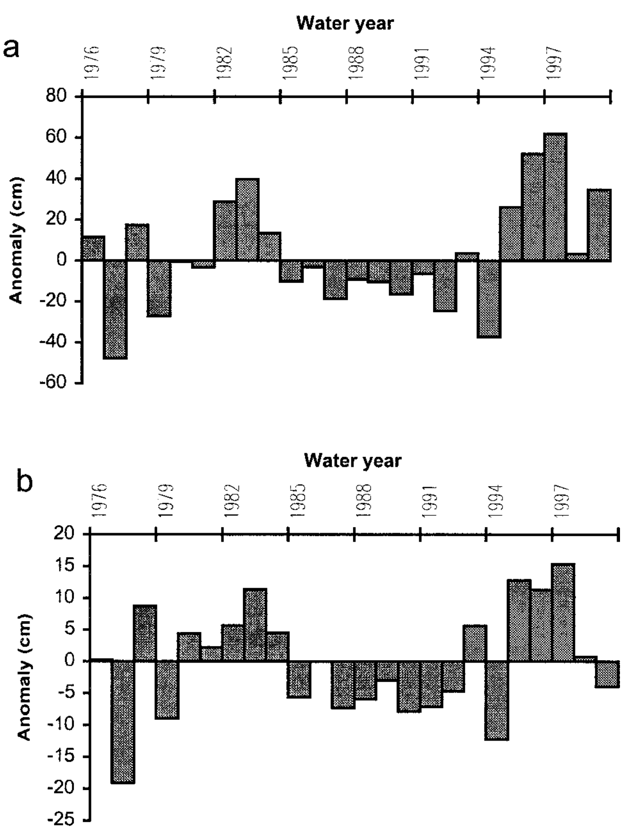


FIG. 2. Annual precipitation anomalies for (a) Willamette Valley and (b) North Central Oregon climate divisions. Long-term (105 yr) annual averages for the Willamette Valley and North Central divisions are 129 and 40.1 cm, respectively.

Second, the importance of an anomaly—discrete or cumulative—depends upon its magnitude relative to some standard measure of typical anomalies (e.g., the standard deviation).

We computed discrete precipitation anomalies using Oregon climate divisional monthly average precipitation data for 1895–2000 (NCDC 2000). The aggregate time series of annual precipitation anomalies for each climate division (Fig. 2) shows that both regions experienced below-normal precipitation during water years 1977, 1979, and for an extended period from 1985 to 1992. During the most severe shortage (1977), annual precipitation in the Willamette Valley and North Central climate divisions was 63% and 52% of the 106-yr average, respectively.

Figure 3 describes the cumulative precipitation anomaly in each climate region for water years 1976–99. Both regions exhibit two periods of depressed cumulative rainfall: roughly 1977–83 and 1987–97. The extended drought period that began in 1985 (see Fig. 2) initiated a decrease in the cumulative anomaly surplus, and ultimately led to the significant shortages in late 1994: a full year's worth in the North Central division, and 80% of the annual mean precipitation in the Willamette Valley.

Rainfall deciles. A large degree of statistical dispersion for precipitation measurements can render the mean a poor reference for typical conditions. In such cases, the median may be used instead of the mean to assess the central tendency of the record. Climatological observations above and below this marker may be divided into 10 quantiles, or deciles. A decile-based system for monitoring meteorological drought was suggested by Gibbs and Maher (1967).

The rainfall deciles methodology begins by ranking observed precipitation totals for the preceding three months against climatological records. If the sum falls within the lowest decile (ninth percentile) of the historical distribution of 3-month totals, then the region is considered to be "drought affected" (Kinninmonth et al. 2000). Such conditions end when either of two things happen:

1) The precipitation measured during the past month already places the 3-month total (for a new period starting that month) in or above the fourth decile (31st percentile or higher).
2) The precipitation total for the past three months is in or above the eighth decile.

The advantage of the decile approach is its computational ease, but this simplicity can lead to conceptual difficulties. For example, it is reasonable for a drought to terminate when observed rainfall is close to or above normal conditions. But minor amounts of precipitation during periods in which little or no precipitation is routine (e.g., summer along the West Coast) can activate the first stopping rule, even though the absolute quantity of precipitation is trivial and does not terminate the water deficit. Therefore, climates with highly seasonal precipitation may not be well suited to rainfall deciles when relying upon the two stopping criteria. A supplemental, third rule (used by the Drought Watch Service of the Australian Bureau of Meteorology) considers total precipitation since the drought began. If this total exceeds the first decile for all such months, then the meteorological drought may be considered to have ended (G. S. Beard 2000, personal communication).

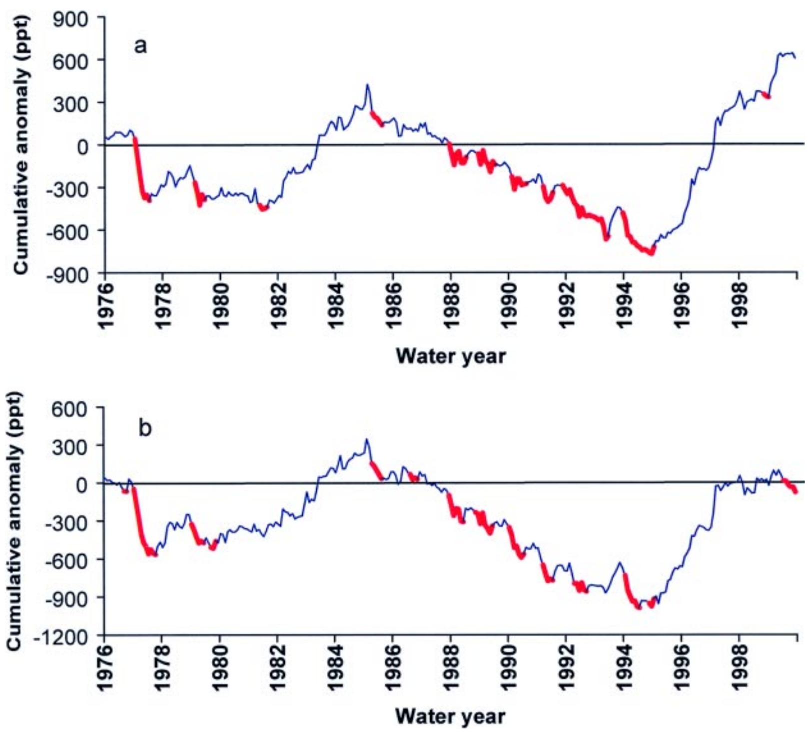


Fig. 3. Cumulative monthly precipitation anomalies for (a) Willamette Valley and (b) North Central Oregon climate divisions. Units are thousandths (ppt) of annual mean precipitation. The final sum of anomalies is not zero because anomalies are computed with respect to long-term (105 yr) means for each month. Red segments indicate decile-identified drought periods.

Oregon monthly precipitation records from 1895 to 2000 were used to construct a decile time series for 1976–99 (NCDC 2000). However, such time series appear erratic and are not particularly instructive to view in their original form, so the decile-indicated drought periods have been highlighted in Fig. 3. The decile-identified droughts in Fig. 3 tend to explain steep declines in the cumulative precipitation anomaly.

Palmer Drought Severity Index. The most prominent index of meteorological drought in the United States is the Palmer Drought Severity Index (PDSI). The PDSI was created with the intent of "measuring the cumulative departure of moisture supply" (Palmer 1965). The PDSI is a dimensionless number typically ranging between 4 and −4, with negative quantities indicating a shortage of water.

The PDSI calculates a series of water balance terms for a generic two-layer soil model, and fluctuations in the hypothetical moisture supply, depending upon observed meteorological conditions, are compared to a reference set of water balance terms. This comparison leads to computation of the dimensionless PDSI. Index values are calculated on an ongoing basis by the NCDC, and monthly PDSI values have been extended back to 1895 (NCDC 2000). Computation of the PDSI is complicated; for an in-depth discussion of the numerical steps, see Alley (1984).

The PDSI is ideally a standardized measure of moisture conditions across regions and time. However, Guttman et al. (1992) determined that routine climatological conditions tend to yield more severe PDSI measures in the Great Plains than other U.S. regions. The shortcomings of regional comparability—which the PDSI was designed to facilitate—are further detailed by Guttman et al. (1992). The PDSI is also imprecise in its treatment of all precipitation as rainfall, as snowfall may not be immediately available as water in the two-layer soil scheme (Hayes 2000).

On the positive side, the PDSI does factor in antecedent conditions and is calculable from basic data. But its empirical nature, coupled with the fact it was developed for U.S. agricultural regions, limits its broad applicability, and as a result the PDSI is not used internationally. Gibbs and Maher (1967) considered its application for Australia but instead recommended rainfall deciles.

Drought Area Index. Like the PDSI, the Drought Area Index (DAI) is a recursive index, in which successive calculations of the index depend upon the prior month's value (Bhalme and Mooley 1980). It can thus consider the persistence of drought. It was developed for assessing moisture during the summer Indian monsoon, when areas of the subcontinent may receive 75% (or more) of the annual rainfall (Bhalme and Mooley 1980). The DAI equation is (Bhalme and Mooley 1980)

$$I_k = 0.5I_{k-1} + \frac{1}{48.55}\frac{P_k - \overline{P_k}}{\sigma_k}, \tag{1}$$

where I = intensity of drought (dimensionless), k = month number, P = monthly precipitation (mm), $\overline{P}$ = average precipitation (mm), and σ= precipitation standard deviation (mm).

The DAI has been developed specifically for India, but can be calibrated for other regions of the world; Oladipo (1985) compared the PDSI and DAI for Nebraska and found that both performed consistently. The DAI is inherently less complicated than the PDSI—the DAI requires only precipitation records, not multiple water balance terms (Bhalme and Mooley 1980).

Rainfall Anomaly Index. The Rainfall Anomaly Index (RAI) was developed by van Rooy (1965), and incorporates a ranking procedure to assign magnitudes to positive and negative precipitation anomalies. The form of the index is

$$\mathrm{RAI} = \pm 3\frac{P - \overline{P}}{\overline{E} - \overline{P}}, \tag{2}$$

where P = measured precipitation, $\overline{P}$ = average precipitation, and $\overline{E}$ = average of 10 extrema.

For positive anomalies, the prefix is positive and $\overline{E}$ is the average of the 10 highest precipitation values on record; for negative anomalies, the prefix is negative and the 10 lowest measurements are used. The index values are judged against a 9-member classification scheme, ranging from extremely wet to extremely dry (van Rooy 1965). Oladipo (1985) found that differences between the RAI and the more complicated indices of Palmer and Bhalme-Mooley were negligible.

Standardized Precipitation Index. The Standardized Precipitation Index (SPI), developed by McKee et al. (1993), interprets observed rainfall as a standardized departure with respect to a rainfall probability distribution function. Precipitation data are assumed to follow an incomplete gamma distribution (Redmond 2000). The original precipitation data are transformed to a normal distribution, which readily allows comparison between distinct locations and analytical computation of exceedance probabilities. Like rainfall deciles, the index requires a long span of precipitation observations; Guttman (1999) recommends at least 50 yr of data for drought periods of 1 yr or less, and more for multiyear droughts.

The dimensionless SPI is computed as the discrete precipitation anomaly of the transformed data, divided by the standard deviation of the transformed data (Agnew 2000). The National Drought Mitigation Center (NDMC) computes the SPI with five running time intervals—1, 3, 6, 9, and 12 months—but the index is flexible with respect to the period chosen. Thus, the SPI can track drought on multiple timescales (Hayes et al. 1999). This powerful feature can provide an overwhelming amount of information unless researchers have a clear idea of the desired intervals. For our drought index comparisons, we selected an SPI interval of 1 month.

As shown in Fig. 4, the general tendencies of the RAI and SPI are quite similar, in contrast to the PDSI, which intermittently possesses large amplitudes. Figure 5 shows scatterplots between the RAI and the each of the other two indices. In both climate divisions, the RAI and SPI exhibit a linear trend, with the lowest correlation coefficient being a remarkable 0.97. The linearity tapers off at lower index values, indicating slightly different responses to more severe drought. In contrast, the PDSI has weaker correlations with the RAI and SPI in both divisions; the RAI–PDSI correlation is 0.59 and 0.39 for the Willamette Valley and North Central divisions, respectively. Correlations between the SPI and PDSI are similarly 0.57 and 0.40 for the Willamette Valley and North Central divisions. This highlights that the PDSI is more of a hydrological index, considering water deficiencies over longer time intervals. Unfortunately, one does not clearly know the timescale of drought that the PDSI is addressing.

The SPI has been in existence less than a decade, so it has not been broadly applied or tested, although it has been used with success in describing drought conditions in Texas and Oklahoma (Hayes et al. 1999; Hayes 2000). Nonetheless, because the SPI relies upon widely measured precipitation data and can probabilistically describe precipitation shortages across any desired timescale, the NDMC and the Western Regional Climate Center (WRCC) advocate it over the traditional PDSI (Redmond 2000).

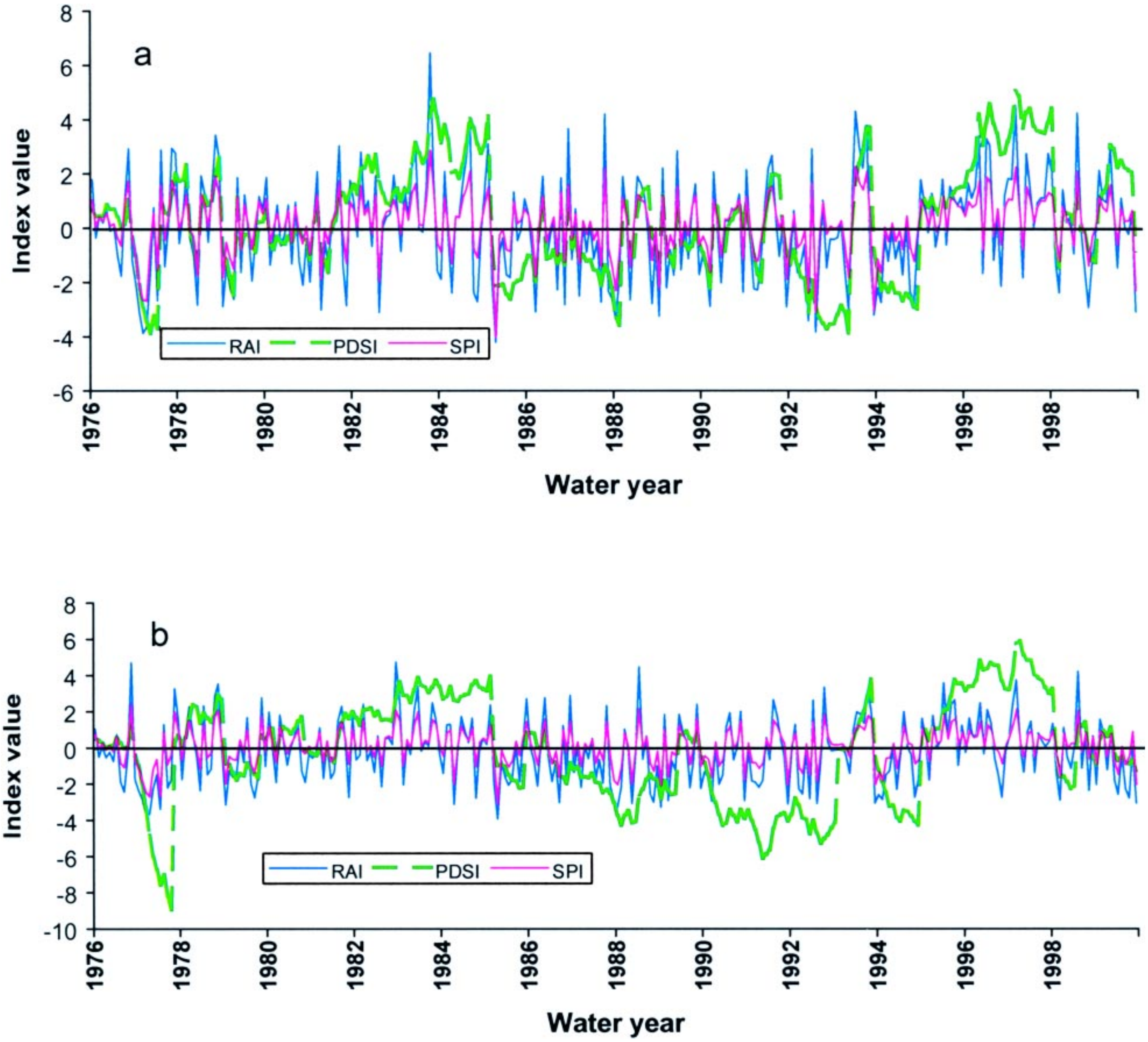


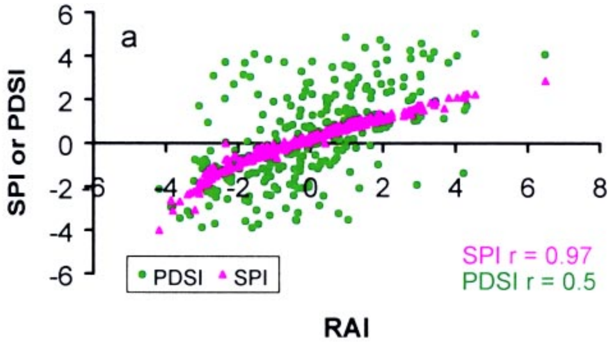
Fig. 4. Time series of RAI, PDSI, and 1-month SPI for (a) Willamette Valley and (b) North Central Oregon climate divisions.

HYDROLOGICAL DROUGHT INDICES.

Hydrological drought is associated with a deficiency in the bulk water supply, which may include water levels in streams, lakes, reservoirs, and aquifers. In this paper, hydrological drought indices were computed using streamflow data. Of the major drought forms, hydrological drought may be the slowest to develop (Soulé 1992). For example, a shortage of snowfall may not manifest itself as depressed runoff until half a year later. This inertia also means that hydrological drought can persist longer than other forms of drought.

Total water deficit. A traditional assessment of hydrological drought is total water deficit, synonymous with the drought severity S. This severity is the product of the duration D, during which flows are consistently below some truncation level (e.g., the hydroclimatic mean), and the magnitude M, which is the average departure of streamflow from the truncation level during the drought period (Dracup et al. 1980). After the drought ends, the total water deficit resets to 0. It should be noted that the severity, duration, and magnitude also appear in the literature as the run sum, run length, and the run intensity, respectively (e.g., Yevjevich 1967). Graphically, hydrological drought severity, duration, and magnitude may be observed in Fig. 6.

Daily streamflow records for the Willamette River (at Salem) and Columbia River (at The Dalles) were



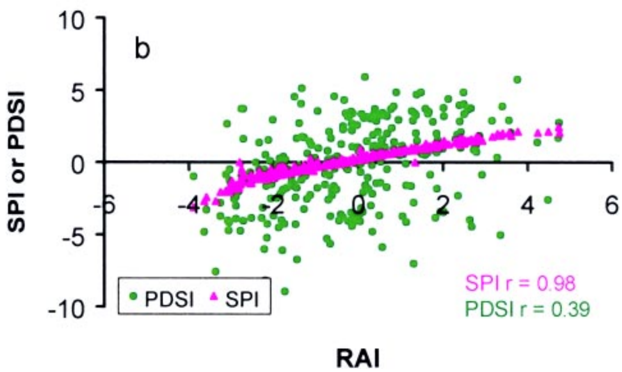


Fig. 5. Scatterplot of RAI vs SPI (1 month) and PDSI for (a) Willamette Valley and (b) North Central Oregon climate divisions. Correlation coefficients noted in lower right of each graph.

obtained from the United States Geological Survey (USGS) for water years 1976–99, and were used to compute monthly discharges (USGS 2000). Records for both rivers extend much earlier, but early data are "unimpaired," or represent stream conditions without the effects of damming or major diversions. Unimpaired data are typically used for hydroclimatic research, but comparisons of monthly and annual discharges during 1976–99 with long-term means for each stream confirmed that the average streamflow has changed due to active river regulation. Since both streams were fully regulated by 1976–99, historical averages would have been inappropriate. Consequently, we have purposefully used an abbreviated period of record (1976–99) to compute the mean and anomalous discharges for the Columbia and Willamette Rivers (Fig. 7). Table 2 documents the total water deficits for sizeable hydrological droughts that afflicted Oregon during 1976–99.

The total water deficit approach summarizes the time-integrated flow conditions at a particular point on a given stream, but representation of a large area with fine resolution requires the concerted examination of numerous watersheds in the region. Drought may not be uniformly intense in all subbasins, so detail is naturally lost by generalizing a region based upon the highest-order stream. Furthermore, large streams with sizeable drainage basins (e.g., the Columbia River) may be communicating climatic information from other regions.

The potential for a single stream to misrepresent water conditions across the entire division was examined by comparing Fig. 7 with annual divisional precipitation (Fig. 2). Not surprisingly, the runoff pattern corresponds well with the annual precipitation, although the general association between the respective graphs is weaker for the North Central division. However, considering that the North Central area occupies just 4% of the Columbia Basin upstream of The Dalles—the location of the streamflow measure-

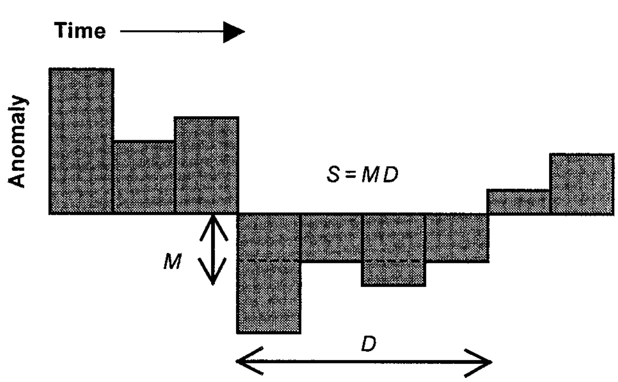


Fig. 6. The drought severity *S* is the product of the duration *D* and the average magnitude *M*. Streamflow anomalies are departures from the mean.

Table 2. Properties of hydrological droughts between water years 1976 and 1999. WY = terminal water year; *D* = duration (yr); *S* = severity (km³); *M* = magnitude (km³ yr⁻¹); Q(%) = percent of annual mean discharge.

WY	*D*	*S*	*M*	Q(%)
Willamette River				
1977	1	11.8	11.8	58%
1981	3	9.3	3.1	45%
1992	8	24.0	3.0	117%
1994	1	8.8	8.8	43%
Columbia River				
1980	4	111.5	27.9	69%
1990	4	101.5	25.4	62%
1995	4	115.0	28.8	71%

ments—the correspondence is good, indicating that the division has climatic characteristics that are generally matched by the bulk of the drainage basin. Hence, the "contamination" of The Dalles streamflow record by precipitation upstream of the North Central division seems to be minimal.

Cumulative streamflow anomaly. A cumulative departure of streamflow from mean conditions can show long-term tendencies in water availability. Figure 8 shows the cumulative streamflow anomaly for both climate divisions. As in the case of the cumulative precipitation anomaly (Fig. 3), steep declines in the cumulative streamflow anomaly represent droughts (see Table 2). For this study, we calculated the cumulative streamflow anomaly with a mean that spanned the same interval as the anomalies. Consequently, the final cumulative anomalies in Fig. 8 are 0.

Palmer Hydrological Drought Severity Index. The Palmer Hydrological Drought Severity Index (PHDI) is very similar to the PDSI, using the identical water balance assessment on a two-layer soil model. The distinction is that the PHDI has a more stringent criterion for the elimination of the drought or wet spell, which results in the index rebounding gradually—more slowly that the PDSI—toward the normal state. Specifically, the PDSI considers a drought finished when moisture conditions begin an uninterrupted rise that ultimately erases the water deficit, whereas the PHDI considers a drought ended when the moisture deficit actually vanishes (Heim 2000). This retardation is appropriate for the assessment of hydrological drought, which is a slower developing phenomenon than meteorological drought.

Surface Water Supply Index. The Surface Water Supply Index (SWSI), developed by Shafer and Dezman (1982), explicitly accounts for snowpack and its delayed runoff. The SWSI is a suitable measure of hydrological drought for regions, such as the mountainous west, where snow contributes significantly to the annual streamflow. Computations require measurements for snowpack, precipitation, streamflow, and reservoir storage, which are assigned nonexceedance probabilities based on the historical record. These percentiles are input to a basin-calibrated SWSI algorithm that considers the typical contribution of each hydrological component to the water supply of the basin. This weighting enables intercomparisons between watersheds (Garen 1992).

We obtained records for the SWSI and PHDI from the Natural Resources Conservation Service (NRCS) and NCDC (2000), respectively. In general, the degree of correlation between SWSI and PHDI values is quite high for both regions (Fig. 9): 0.78 for the North Central division, and 0.70 for the Willamette Valley. Exact comparison of index values is somewhat meaningless, as each takes a different approach to determine the dimensionless magnitude of water surplus and shortage. Qualitatively, however, the degree to which they correlate for the two test regions indicates that both are consistent measures of hydrological drought conditions.

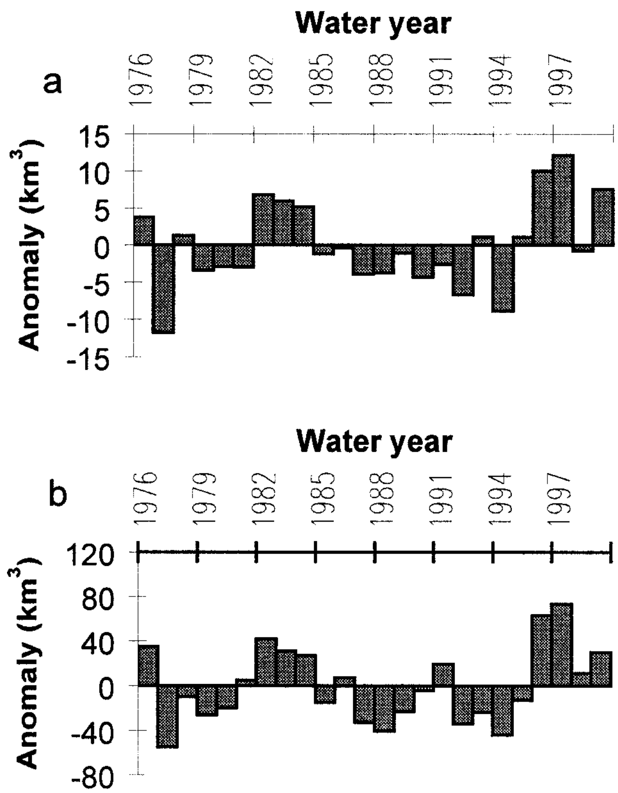


Fig. 7. Annual streamflow anomalies for (a) Willamette River at Salem and (b) Columbia River at The Dalles. Mean annual discharges during the 1976–99 period are 20.5 and 163 km^3, respectively. The 1977 drought was responsible for the lowest water storage levels ever recorded in the Columbia Basin (Richards 1977). Water years 1985–95 saw an extended hydrological drought; Cascade snowpack for water year 1992 was 23% of normal (Balzar 1992). This brought a summer ban on lawn watering, car washing, and the rinsing of paved surfaces in the city of Portland (Glamser 1992). Reduced streamflow even led to the Bonneville Power Administration—caretaker of Columbia River hydroelectricity—to do an unusual reversal and purchase power from California, its usual customer (Murphy 1993).

AGRICULTURAL DROUGHT INDICES. Since most crops are planted, agricultural drought is spe-

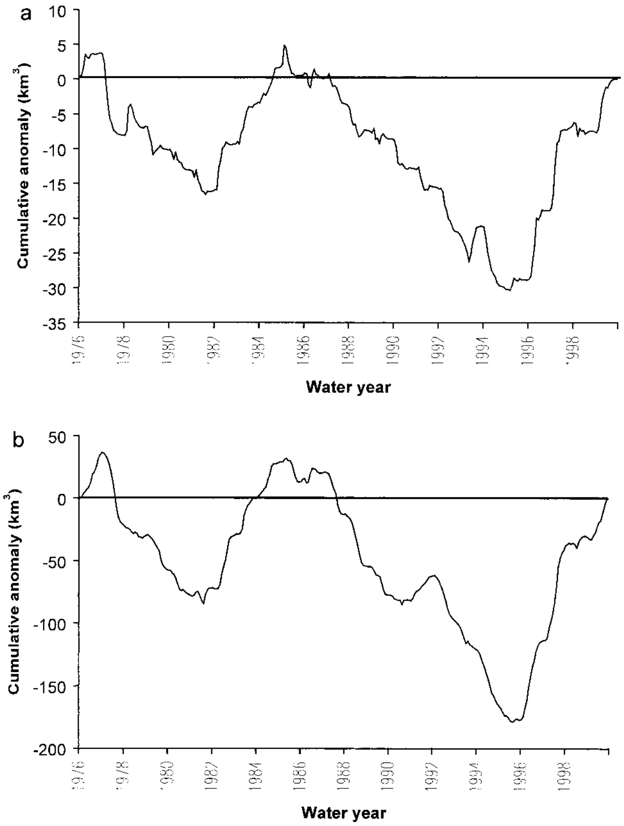


FIG. 8. Cumulative anomalies of monthly streamflow for (a) Willamette River at Salem and (b) Columbia River at The Dalles.

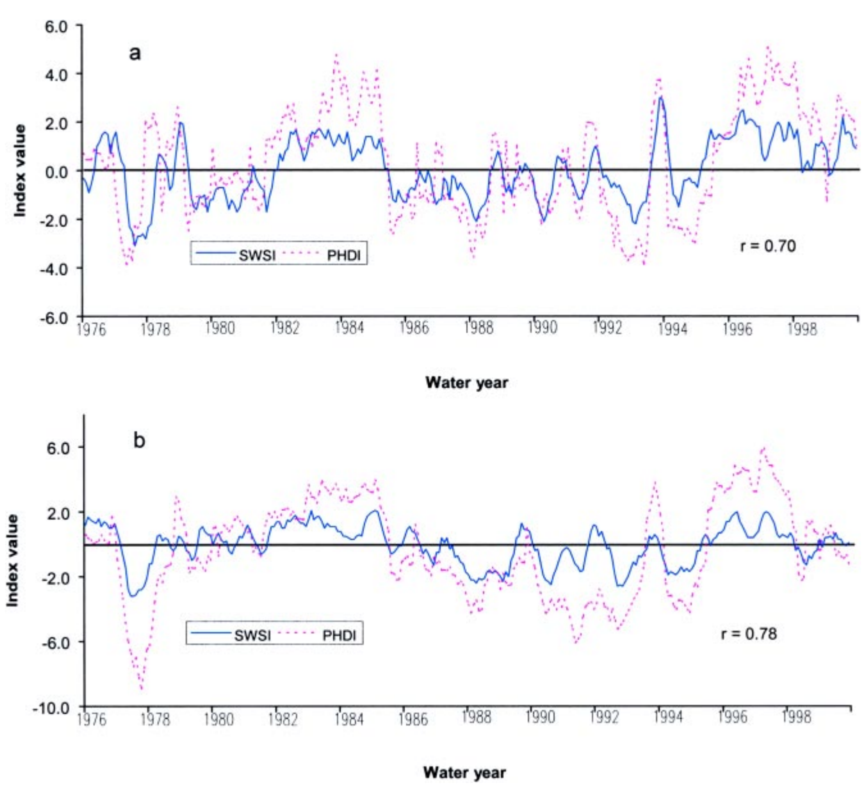


FIG. 9. Time series of monthly SWSI and PHDI values for (a) Willamette Valley and (b) North Central Oregon climate divisions. Correlation coefficients between the indices are given in lower right of each graph.

cifically concerned with cultivated plants, as opposed to natural vegetation. Due to the continuous need of adequate water by plants, agricultural drought may set in rapidly, and can similarly terminate suddenly. It is characterized by important, short-term changes to the volumetric soil moisture (the fraction of pore space that soil water occupies) in the root zone (Rawls et al. 1993; WMO 1975).

Crop Moisture Index. Palmer (1968) developed the Crop Moisture Index (CMI) to monitor short-term changes in moisture conditions affecting crops. The CMI is the sum of an evapotranspiration deficit (with respect to normal conditions) and soil water recharge. These terms are computed on a weekly basis using PDSI parameters, which consider the mean temperature, total precipitation, and soil moisture conditions from the previous week (Palmer 1968).

The CMI can assess present conditions for crops, but it can rapidly vacillate and is a poor tool for monitoring long-term drought (Hayes 2000). For example, a rainstorm may briefly bring crops adequate moisture, even though an extended drought persists. The CMI also begins and ends each growing season near zero, which may be appropriate for botanical annuals, but not for tracking long-term drought. As a consequence, the assessment of agricultural drought is better suited to the related Palmer Z index (Karl 1986).

Palmer Moisture Anomaly Index (Z index). The Palmer moisture anomaly index (Z index) is actually an intermediate term in the computation of the PDSI; it is the moisture anomaly for the current month, without the consideration of the antecedent conditions that characterize the PDSI. The Z index can track agricultural drought, as it responds quickly to changes in soil moisture values. Karl (1986) found that the Z index is preferable for quantifying agricultural drought than the more commonly used CMI. However, like all of the Palmer indices, it suffers from a complicated formulation and computation; it is only slightly less complex than the PDSI itself.

Computed soil moisture. Soil moisture within the growing zone of plants may be measured by a variety of methods, but unfortunately there does not exist a comprehensive, national network of soil moisture monitoring instruments. However, soil moisture may be computed through numerical models that perform a water balance assessment of the soil column, using variables such as precipitation, air temperature, soil temperature, soil porosity, and infiltration. The National Oceanic and Atmospheric Administration's (NOAA's) Climate Prediction Center (CPC) has such computed data available for each of the NCDC climate divisions, on a monthly timescale extending from the present to 1931 (CPC 2000). The details of the numerical model used to compute the soil moisture are given by Huang et al. (1996). One crude simplification in the model is that the adopted soil properties represent a single site in Oklahoma (Huang et al. 1996).

We compared monthly time series of the Z index and surface soil moisture from NCDC and CPC for both climate divisions (NCDC 2000). Over 1976–99, both indices fluctuate considerably, although the Z index varies with larger amplitude. This is because the Z index does not have a mechanism to recognize antecedent conditions; computed soil moisture inherently considers the water balance at the end of the previous month. Correlation between the two indices is very poor: 0.07 and 0.05 for the Willamette Valley and North Central divisions, respectively. To dampen the erratic behavior, 4-month running means of each variable were computed (Fig. 10).

The fact that such adjustments are needed to assure even a marginal basis for comparison indicates that in some ways agricultural drought is the most difficult drought form to judge objectively. Figure 10 confirms that the trend between the Z index and computed soil moisture is not wholly transparent; sometimes the curves are nearly in phase, while during other periods there seem to be lagged relationships, and different magnitude responses to weather forcing. Furthermore, the computed soil moisture appears to be increasing, although this trend has not been studied. Without a national soil moisture monitoring network, computational measures of agricultural drought will remain difficult to judge. The nearest soil moisture stations in Oregon—operated as part of the Natural Resources Conservation Service Soil Climate

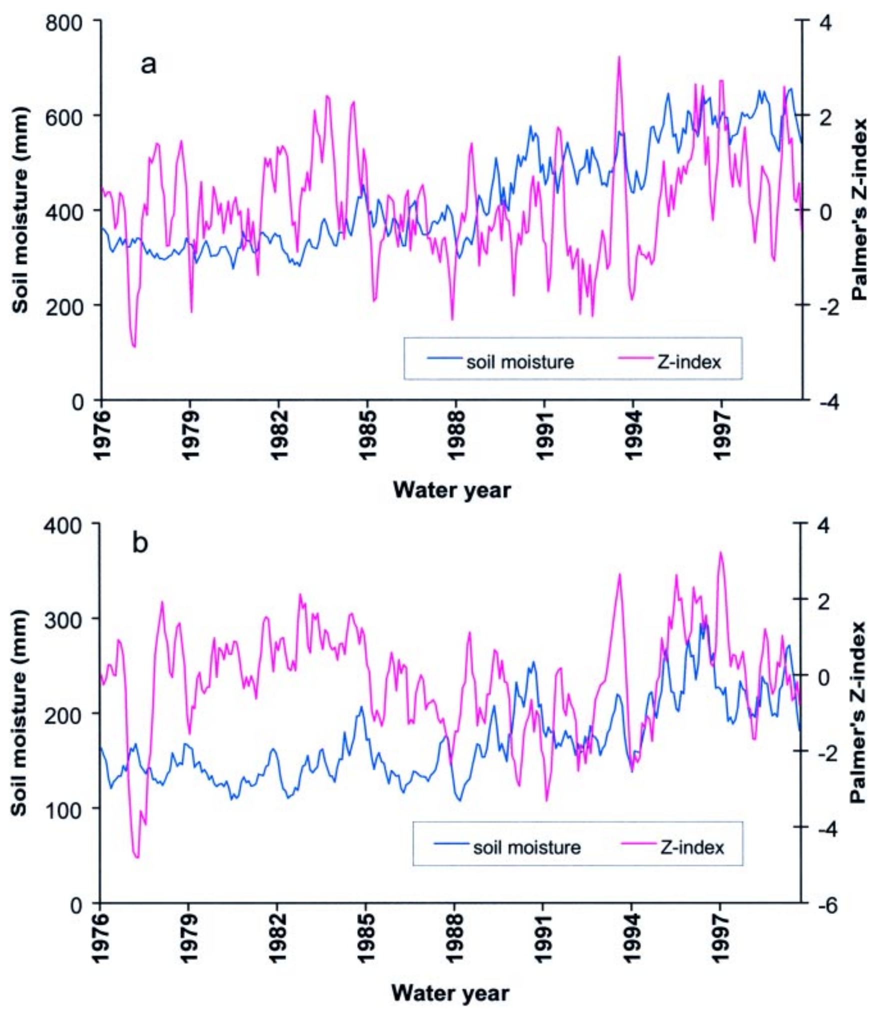


Fig. 10. Time series of 4-month running averages of computed soil moisture and Palmer's *Z* index for (a) Willamette Valley and (b) North Central Oregon climate divisions.

Analysis Network—are in east-central and southeast Oregon, far from the Willamette Valley and North Central divisions and in different climatic regimes (NRCS 2001). Furthermore, a few stations are inadequate to describe soil moisture variability across an entire climate division.

Soil Moisture Anomaly Index. The Soil Moisture Anomaly Index was developed by Bergman et al. (1988) to characterize droughts on a global basis. The method inherently relies upon the moisture accounting method of Thornthwaite (viz., the tracking of precipitation and potential evapotranspiration), and operates within a two-layer soil model used to track the movement of water, ultimately resulting in a running assessment of percent soil saturation. Further explanations of the procedure are given by Bergman et al. (1988). Simulations suggest that Soil Moisture Anomaly Index values change at a rate centered between the rapid CMI and the relatively slow PDSI (Bergman et al. 1988).

EVALUATION SCORES. The strengths and weaknesses of the various drought indices—and how those characteristics relate to the adopted evaluation criteria—were considered in the assignment of the evaluation scores for each index. The six raw scores, each ranging between 1 and 5, were multiplied by their respective weights (Table 1), and the sums of the weighted scores are presented in descending order in Table 3. In all cases, indices were ranked according to the form of drought that they seek to resolve. As shown in Table 3, application of weighted selection criteria determines that the overall superior drought indices—of the subset of drought indices discussed in this paper—are rainfall deciles, total water deficit, and computed soil moisture for the meteorological, hydrological, and agricultural drought

Table 3. Comparison of drought indices across evaluation criteria.

Index	Weighted total	Raw scores (1–5)					
		Robustness	Tractability	Transparency	Sophistication	Extendability	Dimensionality
Meteorological drought							
Rainfall deciles	116	5	3	4	3	5	4
SPI	115	5	2	3	5	5	4
Cumulative precip. anomaly	97	3	4	4	2	3	5
RAI	94	3	4	4	2	4	2
DAI	70	2	3	2	3	3	1
PDSI	61	2	1	1	4	4	1
Hydrological drought							
Total water deficit	102	3	4	5	2	3	5
Cumulative streamflow anomaly	89	2	4	4	2	3	5
SWSI	75	4	1	2	3	2	3
PHDI	58	2	1	1	4	3	1
Agricultural drought							
Computed soil moisture	102	4	1	5	4	3	5
Soil moisture anomaly index	83	3	2	3	3	3	4
Z index	77	3	2	2	4	3	1
CMI	55	2	1	1	4	2	1

forms, respectively. For meteorological drought, the SPI also emerges as a highly valuable estimator of drought severity.

REFERENCES

Agnew, C. T., 2000: Using the SPI to identify drought. *Drought Network News,* **12,** 6–11.

Ahrens, C. D., 1994: *Meteorology Today: An Introduction to Weather, Climate, and the Environment.* 5th ed. West Publishing, 591 pp.

Alley, W. M., 1984: The Palmer Drought Severity Index: Limitations and assumptions. *J. Climate Appl. Meteor.,* **23,** 1100–1109.

Balzar, J., 1992: Dry Northwest gets a taste of water rules, fire concerns. *Los Angeles Times,* 3 June, sec. A.

Bergman, K. H., P. Sabol, and D. Miskus, 1988: Experimental indices for monitoring global drought conditions. *Proc. 13th Annual Climate Diagnostics Workshop,* Cambridge, MA, U.S. Dept. of Commerce, 190–197.

Bhalme, H. N., and D. A. Mooley, 1980: Large-scale droughts/floods and monsoon circulation. *Mon. Wea. Rev.,* **108,** 1197–1211.

CPC, cited 2000: U.S. soil moisture monitoring. [Available online at http://www.cpc.ncep.noaa.gov/soilmst/.]

Dracup, J. A., K. S. Lee, and E. G. Paulson Jr., 1980: On the definition of droughts. *Water Resour. Res.,* **16,** 297–302.

Foley, J. C., 1957: *Droughts in Australia: Review of Records from Earliest Years of Settlement to 1955.* Australian Bureau of Meteorology, Bull. 43, 281 pp.

Garen, D. C., 1992: Revised Surface-Water Supply Index for the western United States. *J. Water Resources Plan. Manage.,* **119,** 437–454.

Gibbs, W. J., and J. V. Maher, 1967: *Rainfall Deciles as Drought Indicators.* Australian Bureau of Meteorology, Bull. 48, 37 pp.

Glamser, D., 1992: Dry Seattle turn to fewer flushes, faster showers. *USA Today,* 12 May, sec. A.

Guttman, N. B., 1999: Accepting the Standardized Precipitation Index: A calculation algorithm. *J. Amer. Water Resour. Assoc.,* **35,** 311–322.

——, ——, J. R. Wallis, and J. R. M. Hosking, 1992: Spatial comparability of the Palmer Drought Severity Index. *Water Resour. Bull.,* **28,** 1111–1119.

Hayes, M. J., cited 2000: Drought indices. [Available online at http://enso.unl.edu/ndmc/enigma/indices.htm.]

——, ——, M. D. Svoboda, D. A. Wilhite, and O. V. Vanyranko, 1999: Monitoring the 1996 drought using the Standardized Precipitation Index. *Bull. Amer. Meteor. Soc.,* **80,** 429–438.

Heim, R. R., Jr., 2000: Drought indices: A review. *Drought: A Global Assessment,* D. A. Wilhite, Ed., Routledge, 159–167.

Huang, J., H. van den Dool, and K. P. Georgakakos, 1996: Analysis of model-calculated soil moisture over the United States (1931–93) and application to long-range temperature forecasts. *J. Climate,* **9,** 1350–1362.

Karl, T. R., 1986: The sensitivity of the Palmer Drought Severity Index and Palmer's Z-index to their calibration coefficients including potential evapotranspiration. *J. Climate Appl. Meteor.,* **25,** 77–86.

Kinninmonth, W. R., M. E. Voice, G. S. Beard, G. C. de Hoedt, and C. E. Mullen, 2000: Australian climate services for drought management. *Drought: A Global Assessment,* D. A. Wilhite, Ed., Routledge, 210–222.

Korn, V. G., Ed., 2001: *2000–2001 Oregon Agriculture & Fisheries Statistics.* Oregon Department of Agriculture, 85 pp.

McKee, T. B., N. J. Doesken, and J. Kleist, 1993: Drought monitoring with multiple timescales. Preprints, *Eighth Conf. on Applied Climatology,* Anaheim, CA, Amer. Meteor. Soc., 179–184.

Murphy, D. E., 1993: Miss the drought? Try the Northwest. *Los Angeles Times,* 13 April, sec. A.

NCDC, cited 2000: Climate division: Temperature–precipitation–drought data. [Available online at http://www.ncdc.noaa.gov/onlineprod/drought/ftppage.html.]

NRCS, cited 2001: Soil Climate Analysis Network. [Available online at http://www.wcc.nrcs.usda.gov/scan/index2.html.]

Oladipo, E. O., 1985: A comparative performance analysis of three meteorological drought indices. *J. Climatol.,* **5,** 655–664.

Palmer, W. C., 1965: Meteorological Drought. Weather Bureau, Research Paper No. 45, U.S. Dept. of Commerce, Washington, DC, 58 pp.

——, 1968: Keeping track of crop moisture conditions, nationwide: The new Crop Moisture Index. *Weatherwise,* **21,** 156–161.

Rasmussen, E. M., R. E. Dickinson, J. E. Kutzbach, and M. K. Cleaveland, 1993: Climatology. *Handbook of Hydrology,* D. R. Maidment, Ed., McGraw-Hill, 2.1–2.44.

Rawls, W. J., L. R. Ahuja, D. L. Brakensiek, and A. Shirmohammadi, 1993: Infiltration and soil water movement. *Handbook of Hydrology,* D. R. Maidment, Ed., McGraw-Hill, 5.1–5.51.

Redmond, K., 1991: Climate monitoring and indices. *Proc. Drought Management and Planning Seminar and Workshop,* Denver, CO, International Drought Information Center, University of Nebraska, 29–33.

——, 2000: Integrated climate monitoring for drought detection. *Drought: A Global Assessment,* D. A. Wilhite, Ed., Routledge, 145–158.
Richards, B., 1977: Drought dims Northwest; Dwindling dam levels may force blackouts. *Washington Post,* 6 April, sec. A.
Shafer, B. A., and L. E. Dezman, 1982: Development of a Surface Water Supply Index (SWSI) to assess the severity of drought conditions in snowpack runoff areas. *Proc. 50th Western Snow Conf.,* Reno, NV, 164–175.
Soulé, P. T., 1992: Spatial patterns of drought frequency and duration in the contiguous USA based on multiple drought event definitions. *Int. J. Climatol.,* **12,** 11–24.
USGS, cited 2000: Oregon NWIS-W data retrieval. [Available online at http://waterdata.usgs.gov/nwis-w/OR/.]
van Rooy, M. P., 1965: A rainfall anomaly index independent of time and space. *Notos,* **14,** 43–48.
Wilhite, D. A., 2000: Drought as a natural hazard: Concepts and definitions. *Drought: A Global Assessment,* D. A. Wilhite, Ed., Routledge, 3–18.
——, and M. H. Glantz, 1985: Understanding the drought phenomenon: The role of definitions. *Water Int.,* **10,** 111–120.
WMO, 1975: Drought and Agriculture. WMO Tech. Note 138, 127 pp.
WRCC, cited 2001: WRCC Climate Division Monitoring Products. [Available online at http://www.wrcc.dri.edu/divisional.html.]
Yevjevich, V. M., 1967: An objective approach to definitions and investigations of continental hydrologic droughts. Colorado State University, Hydrology Paper 23, Fort Collins, CO, 18 pp.