Objective Quantification of Drought Severity and Duration

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ABSTRACT

Common weaknesses of current drought indexes were analyzed. First, most of the current indexes are not precise enough in detecting the onset, end, and accumulated stress of drought. Second, they do not effectively take into account the aggravating effects of runoff and evapotranspiration, which build up with time. Third, they have a limited usefulness in monitoring ongoing drought because they are based on a monthly time step. Fourth, most of them fail to differentiate the effects of drought on surface and subsurface water supply.

A new series of indexes are proposed to solve these weaknesses and to improve drought monitoring. In the new indexes, daily, rather than monthly, time steps are used. A new concept, effective precipitation (EP), the summed value of daily precipitation with a time-dependent reduction function, is proposed as a basic tool.

Three additional indexes complement EP. The first index is each day's mean of EP (MEP). This index shows climatological characteristics of precipitation as a water resource for a station or area. The second index is the deviation of EP (DEP) from the MEP. The third index is the standardized value of DEP (SEP). By using these three indexes, consecutive days of negative SEP, which can show the onset, the ending date, and the duration of a water deficit period is categorized.

With the duration categorized, four additional indexes that can show drought severity are calculated: 1) accumulation of consecutive negative SEP, which shows the duration and severity of precipitation deficit together; 2) accumulated precipitation deficit, which shows precipitation departure from the normal during a defined period; 3) precipitation for the return to normal; and 4) effective drought index, a standardized index that can be used to assess drought severity worldwide. The merits and weaknesses of each index are compared. New quantified definitions on drought and its onset, end, and duration are proposed.

These indexes were tested in the High Plains region of the United States from 1960 to 1996. The results were compared to historical reports of drought. From this analysis, it was concluded that the new indexes not only advanced objectivity, but also offered a number of advantages in practical use. These are 1) a more precise determination of drought duration, 2) the usefulness in monitoring an ongoing drought, and 3) the variety of ways a drought's characteristics can be described.

1. Introduction

The study of drought can be classified into four categories. The first category deals with the causes of drought and seeks an improved understanding of atmospheric circulation associated with drought occurrences. The second category is directed at understanding the frequency and severity of drought in order to characterize the probability of occurrence of droughts of various magnitudes. The third category attempts to describe and understand the impacts of drought. This category focuses on the costs and losses associated with drought. These losses may be classified as economic, social, or environmental and may be either direct or indirect. The final category looks at responses, appropriate mitigation, and preparedness strategies and focuses on a reduction of the impacts associated with drought.

The first category evolved with the help of globally gridded meteorological data for the late twentieth century. Byun (1996), Byun et al. (1992a,b), Chu et al. (1993), Namias (1991), Trenberth and Branstator (1992), and a few more provide examples of research in this category. Most studies on the second category were conducted together with studies on the third category. Doornkamp et al. (1980), Landsberg (1982), Ratcliff (1978), Riebsame et al. (1991), Palmer (1965), and McKee et al. (1993, 1995) are examples of these studies. The fourth category has progressed in recent years and

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TABLE 1. Characteristics of current drought indices.

Name	Factors used	Timescale	Main concept	Source, year created
PDSI	*r*, *t*, et, sm, rf	m (2w)	Based on moisture input, output, and storage. Simplified soil moisture budget.	Palmer (1965)
RAI	*r*	m, yr	Compared *r* to arbitrary values of +3 and −3, which are assigned to the mean of 10 extreme + and − anomalies of *r*.	Rooy (1965)
Deciles	*r*	m	Dividing the distribution of the occurrences over a long-term *r* record into sections, each represents 10%.	Gibbs and Maher (1967)
CMI	*r*, *t*	w	Like the PDSI, except considering available moisture in top 5 ft of soil profile.	Palmer (1968)
BMDI	*r*	m, yr	Percent departure of *r* from the long-term mean.	Bhalme and Mooley (1980)
SWSI	P, sn	m	Weighted average of standardized anomalies of the main elements of the water budget.	Shafter and Dezman (1982)
SMDI	sm	yr	Summation of daily sm for a year.	Hollinger et al. (1993)
CSDI	et	s	Summation of the calculated et divided into possible et during the growth of specific crops.	Meyer et al. (1993)
SPI	*r*	3 m, 6 m, 12 m, 24 m, 48 m	Standardized anomaly for multiple timescales after mapping probability of exceedance from a skewed distribution.	McKee et al. (1993)
RI	*r*	yr, c	Patterns and abnormalities of *r* on a continental scale.	Gommes and Petrassi (1994)
RDI	*r*, *t*, sn, st, rs	m	Supply element–demand element.	Weghorst (1996)

Abbreviations: P—factors used in PDSI, *r*—precipitation, et—evapotranspiration, *t*—temperature, sm—soil moisture, rf—runoff, sn—snowpack, st—streamflow, rs—reservoir storage, w—week, m—month, s—season, yr—year, c—century, 3 m—3 months.

is evolving rapidly. The establishment of the National Drought Mitigation Center in Lincoln, Nebraska, is an example of proactive rather than reactive philosophy. Wilhite (1997a,b, 1996, 1993, 1991, and 1986), Wilhite et al. (1986), and Wilhite and Rhodes (1994) are examples of research in this category.

In spite of these studies, quantifying drought intensity and duration continues to be a problem. The present study focuses on the definition of drought and the quantification of its intensity and duration.

The general concepts that used today as meteorological definitions on dry periods are 1) consecutive days with no precipitation, 2) consecutive days with little precipitation, or 3) little precipitation during a specific period of time (Byun and Han 1994; Broccoli and Manabe 1992; Kim 1968; Steila 1986). The definitions of ''consecutive days,'' ''specific period,'' ''no precipitation,'' and ''little precipitation'' are quantified by empirically or subjectively rather than objectively estimated values. Actually, in defining little precipitation, some meteorologists and climatologists generally regard it as ''daily precipitation less than 2 mm,'' but others regard it as less than ''5 mm.'' Also, on the definition of no precipitation, some view it as daily precipitation less than a trace, while others view it as less than 2 mm because it has little impact on the ecosystem. On the definition of consecutive days, some use a period of more than 15 consecutive days (Huschke 1970), but others use a time frame of 25 days (Steila 1986). For the definition of ''little precipitation during a specific period of time,'' some use a monthly unit, while others use seasons or other periods (Byun et al. 1992a,b; Byun and Han 1994).

Aside from these definition on dry period, general meteorological droughts are defined over a monthly or seasonal timescale as shown in Table 1. Drought may also be defined in hydrological, agricultural, and socioeconomic terms also. Factors in defining drought may include deforestation, land degradation, and construction of dams. They may also include precipitation shortages, pack snow, differences between actual and potential evapotranspiration, soil water deficits, reduced ground water, or reservoir level and reduction in power production. It is important to recognize that almost all of these factors are not independent but related to each other, and meteorological change (especially temperature and precipitation) can affect all of these (Wilhite and Glantz 1987).

Most drought indexes are based on meteorological or hydrological variables. They include the Palmer Drought Severity Index (PDSI; Palmer 1965), Rainfall Anomaly Index (RAI; van Rooy 1965), deciles (Gibbs and Maher 1967), Crop Moisture Index (CMI; Palmer 1968), Bhalme and Mooly Drought Index (BMDI; Bhalme and Mooley 1980), Surface Water Supply Index (SWSI; Shafer and Dezman 1982), National Rainfall Index (RI; Gommes and Petrassi 1994), Standardized Precipitation Index (SPI; McKee et al. 1993, 1995), and Reclamation Drought Index (RDI; Weghorst 1996). The Soil Moisture Drought Index (SMDI; Hollinger et al. 1993) and Crop-Specific Drought Index (CSDI; Meyer et al. 1993; Meyer and Hubbard 1995) appeared after the CMI. Furthermore, the CSDI is divided into a Corn Drought Index (Meyer et al. 1993) and Soybean Drought Index (Meyer and Hubbard 1995). Besides of these indexes, indexes of Penman (1948), Thornthwaite (1948, 1963), and Keetch and Byram (1968) were used in limited cases (Steila 1986; Hayes 1996). The characteristics of each index are summarized in Table 1. Of all the indexes, the PDSI is still the most widely used and recognized index on an operational bases. This study evaluates the characteristics of these indexes, assesses their limitations, and proposes new indexes as a solution.

2. Shortcomings of current indexes

a. Defining the period of water deficit

Drought occurs with the deficiency of water (mainly land surface and ground) resources from the climatological mean. It is not only the deficiency at a specific time but also the consecutive occurrences of deficiencies that define severity. Therefore, drought indexes should be calculated with the concept of ''consecutive'' occurrences of water deficiency. But most current indexes assess only the deficiency of water from the climatological mean for some predefined duration. Furthermore, no objective method defining duration is found.

b. Time unit of assessment

Most current drought indexes use a monthly or longer time period as a unit, as shown in Table 1. Only a few indexes (CMI, sometimes PDSI; Finger et al. 1985) use a weekly unit. No index uses a daily unit. But the daily unit should be used because water amount of an affected drought region can return to normal conditions with only a day's rainfall. For example, if there were heavy rains only on 1 July and 31 August, sixty days of no precipitation from 2 July to 30 August may not be detected by a monthly index in spite of the possibility of severe damage. If there were heavy rain only on 15 July and 15 August, thirty days of dry period can be detected and this is not a rare case. A dry period lasting less than 1 month is not unimportant. In some countries (United Kingdom), a period as short as 15 days with little rain has been defined as a dry spell.

Furthermore, it is important that drought intensity be reevaluated frequently. This would allow the general public to prepare for the risks. Then a daily index is inevitable especially in areas where a lot of precipitation normally occurs and precipitation is the main source of water. An index with a monthly unit, on the other hand, can be calculated only at the end of month.

c. Storing term of water resources

Drought impacts result from a deficiency of water in surface or subsurface components of the hydrologic system. Soil moisture is usually the first component of the hydrologic system to be affected. As the duration of the event continues, other components will be affected. Thus, the impacts of drought gradually spread from the agricultural sector to other sectors and finally a shortage of stored water resources becomes detectable. Then the causes of drought can be divided into two kinds: a shortage of soil moisture, and shortages of water stored in other reservoirs. It is not easy to imagine drought damages that are not associated with these two categories.

Soil dryness is influenced by a recent deficiency of precipitation, and water resource deficiencies in reservoirs or other sources are affected by much longer-term precipitation totals. So drought indexes should categorize these two separately, but current drought indexes except PDSI and SWSI do not divide the two.

d. Considering the diminishing of water resources over time

After rainfall, soil moisture diminishes over time as a function of a runoff and evapotranspiration ratio. Soil moisture is reduced on a daily basis. Also, when considering water in the reservoir, daily depletion should be taken into account because water diminishes every day through the long term. It is apparent that water from rain that fell 11 months ago can remain in the reservoir and that the amount has been reduced day by day.

Therefore, simple summation of precipitation may not provide good results in detecting the deficiency of water. A time-dependent reduction function is needed to estimate the current water deficiency. However, most current drought indexes use simple summation of precipitation.

e. Data used

Besides precipitation, current drought indexes are calculated from data including soil moisture, waterway inflow and outflow, evaporation, and evapotranspiration. Soil moisture conditions, which have been observed from the early fifteenth century in Korea, for example, have been observed systematically at several U.S. locations since the early 1980s (Hollinger et al. 1993). Someone says that it is since the 1950s in Iowa. But at most stations, soil moisture has been estimated rather than observed from precipitation (e.g., Schemm et al. 1992). Besides the soil moisture, many elements and parameters (e.g., runoff, evapotranspiration, etc.) must be estimated for the calculation of drought indexes. During estimation, two problems arise. First, simplification is inevitable because of wide variability in soil characteristics and topography. Second, the important fact that the major origin of water included in these parameters is rainfall, is disregarded. This means that, for example, precipitation and soil moisture cannot be used together with the same weight for the indexation because the main source of water in soil moisture is precipitation itself.

Olapido (1985), after comparison of the PDSI (Palmer 1965) with the RAI (van Rooy 1965) and BMDI (Bhalme and Mooley 1980), concluded that using only precipitation data is better for detecting meteorological drought. Alley (1984) voiced the same opinion. Using precipitation data alone for drought indexes is not only good enough but also has other benefits. It can be collected at more sites than any other data. It is the key variable in drought definitions because all drought stems from precipitation shortages. It needs the least observations. Also, precipitation data is available for a longer time period than any other meteorological data.

f. Various information

When drought occurs, the general public wants to know how long the drought has lasted, how long it will last, how much deficit of water occurred, and how much rainfall is needed to return to normal conditions. The problems connected with predicting the beginning and end of drought are beyond the scope of this study, and no good solutions to these questions have been introduced yet. Several indexes (PDSI, SPI, deciles) can provide information about the probability for a return to normal conditions based on the precipitation deficiency and normal climatology. But this study proposes the use of more information.

3. Calculation and application of effective precipitation

a. Calculation of EP

To represent daily depletion of water resources, a new concept, effective precipitation (EP) is proposed by the next three equations:

$$\mathrm{EP}_i = \sum_{m=1}^{i} P_m^{-m/i} \tag{1}$$

$$\mathrm{EP}_i = \sum_{n=1}^{i} \left[\left(\sum_{m=1}^{n} P_m \right) \Big/ n \right] \tag{2}$$

$$\mathrm{EP}_i = \sum_{m=1}^{i} \left[a(i - m + 1)P_m \Big/ \left(\sum_{n=1}^{i} n \right) \right], \tag{3}$$

where

i = duration of summation (DS),
P_m = precipitation of m days before,
a = constant [if i is 365, 100 is used as a value of a for the valance with (1)].

Equation (1) is derived from the equation $d(\mathrm{EP})/dt = -C(\mathrm{EP})$, where C is a constant and t is day. In other words, this equation shows that daily depletion of EP is proportional to the amount of EP. Equation (2) is derived from the concept that the precipitation m days before is added to total water resources as a form of average precipitation of m days. Equation (3) is derived by the empirical method. The effect of each equation is illustrated in Fig. 1.

The DS is the number of the days whose precipitation is summed for calculation of drought severity. In this study, two dummy values of DSs are used for the detection of real DSs. One is 365 and the other is 15. The reason for the selection of dummy numbers 365 and 15 is in the next section. How DS is used, which is one of the most important parts of this study, is also in sections 4, 5, 6.

For a better understanding of these equations, let's assume a case in which i (DS) is equal to 2. In (1), EP_2 becomes $[P_1 \exp(-1/2) + P_2 \exp(-2/2)]$. In (2), because m varies from 1 to 2, EP_2 becomes $[P_1 + (P_1 + P_2)/2]$. In (3), EP_2 becomes $[(2P_1 + P_2)/3]$. Each equation's weight differences to the EP along the day pass are shown in Fig 1. Equation (1) is not appropriate to represent the depletion of water resources because it shows, in spite of its good physical meaning, only a little change of weight through the period. Equation (2) shows steep changes of weight at the former part of the curve. But (3) shows slow changes of weight through the whole period.

Then, what rate of change of weight is the best? The results from various kinds of rainfall-runoff model by hydrologists show that the change of runoff ratio is the steepest just after rainfall (Lee 1998; Shim et al. 1998). Because this study takes into account the water resources in reservoir also, however, (2) and (3) are usable.

Except these equations, many other equations may show the depletion of water resources over time. The choice of the best equation remains an unsolved problem because many parameters, like topography, soil characteristics, ability to keep water in reservoirs, air temperature, humidity, and wind speed, must be considered

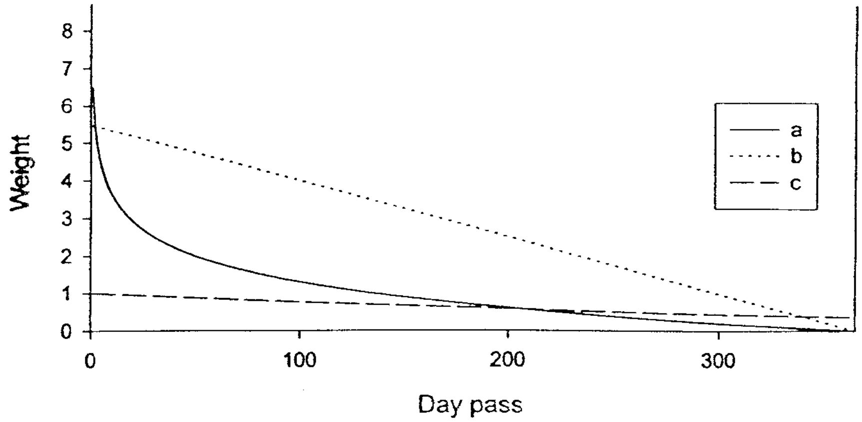

FIG. 1. Variation of the weight of precipitation to EP along the day pass, which is considered in (a) Eq. (2), (b) Eq. (2), and (c) Eq. (1). The abscissa axis reflects day pass. Ordinate axis shows a multiplied number to the rainfall amount along the day-pass to calculate the EP. For example, in (a), precipitation 1 day before being added to the EP after having been multiplied by 6.4, but one 365 days before is added after multiplication by 1/365. Here 6.4 is the sum of $1/n$ when n varies from 1 to 365.

precisely together to represent the depletion of water resources in nature by runoff and evapotranspiration etc. Also hydrological rainfall–runoff model itself is not appropriate in this study because it considers runoff during short timescales but does not consider factors like evapotranspiration, etc., and because it has restrictions [as pointed out by Singh (1988)]. In this situation, it is important that random-day precipitation is successfully reproduced as a series of daily extensive measure named EP by these equations. Then (2) and (3) are tested with observed precipitation data.

b. On dummy DS

The first important problem in detecting drought severity is to determine how long the precipitated water has been in deficit. A dummy value of 365 was chosen initially, for 1 yr is the most dominant precipitation cycle worldwide. EP_{365} can be a representative value of the total water resources available or stored for a long period, named EP_1 for short.

TABLE 2. Characteristics of each index in the EP series.

Name	Calculation	Simplified meaning
EP	Eqs. (1), (2), (3)	Stored water quantity
MEP	30-yr mean of EP for each calendar day	Climatological mean of water quantity
DEP	Deviation of MEP from EP	From climatological mean, the deficit of water quantity
SEP	DEP divided by one standard deviation of EP	From climatological mean, standardized deficit of water quantity
AVG	Average	Simple average of precipitation

Otherwise, EP_{15}, named EP_s, can be a representative value of the total water resources stored for a short period in soil. A dummy value of 15 was chosen arbitrarily because no other exact values are known. In this study, explanations are focused on EP_1. From this point all indexes without ‘‘s’’ denote those with ‘‘1.’’

c. Application using EP

Once the daily EP of a station is computed, a series of calculations can be made to highlight different characteristics of the station's water resources, as listed in Table 2. Because EP needs to be compared to climatological data and because precipitation at most stations has a strong annual variation, EPs are averaged along the day number (i.e., by calendar day). The first step beyond EP is shown as the mean of EP (MEP). This number illustrates the climatological characteristics of water resources. But, because a strong daily variation of MEP is not helpful for practical use, a 5-day running mean is applied.

The second step is to calculate the deviation of EP (DEP) from the MEP:

$$\mathrm{DEP} = \mathrm{EP} - \mathrm{MEP}. \tag{4}$$

The DEP shows the deficiency or surplus of water resources for a particular date and place.

The next step is the calculation of the standardized value of DEP (SEP):

$$\mathrm{SEP} = \mathrm{DEP}/\mathrm{ST(EP)}, \tag{5}$$

where ST(EP) denotes the standard deviation of each day's EP. In this case also, each date's (i.e., each calendar day's) standard deviation is used in incorporating a 5-day running mean to smooth daily variation. SEP enables one location's drought severity to be compared to

TABLE 3. New definitions.

Name	Definition
Dry duration	Period of consecutive negative values of SEP (or SEP_{15}).
Duration of summation (DS)	Dry duration added to 365 (or 15) on D day. Number of days whose precipitation is summed into the calculation. Here "i" in (1), (2), and (3).
Drought duration	Period that the EDI shows less than −1.0. Dry duration between drought durations is included if no positive EDI is involved.

another location's, regardless of climatic differences. But a SEP on 1 January 1996 that is calculated from the 365-day precipitation of 1995, shows only the water deficiency or sufficiency of 1 January 1996. It does not take into account any drought situations before the 365-day period. It also does not take into account a small-scale drought that occurred in 1995, the period of which is less than 365 days. In other words, if there had been a 2-yr severe drought from 1 January 1994 to 31 December 1995, the SEP of 1 January 1996 could not detect this drought intensity because the SEP accounts for only 1-yr of data. Time series of SEP from 1 January 1995 to 1 January 1996 can only provide a clue to detect this long-lasting drought period. Therefore, defining the duration of the precipitation deficit period is important.

d. *Defining dry duration and DS*

Because negative values of DEP or SEP denote precipitation is below normal, periods of consecutive negative values in DEP and SEP denote consecutive drier periods than normal. A dry duration then can be defined as the period of consecutive negative values of SEP. Also, DS can be defined as the sum of dummy DS and the passed day in dry duration. For example, if 35 days of consecutive negative SEP occurred at 5 June, the dry duration of 5 June is 35. The DS of 5 June is 399 (365 + 35 − 1) and the DS of 4 June is 398 (365 is added because dry duration was defined by the use of 365-day precipitation). Drought duration should be different from dry duration because drought means not only a "long-lasting" but also a "severe" water deficiency. Table 3 and the following section will address this problem again.

4. Quantification of drought severity

Once the DS is found, many kinds of daily drought severity indexes can be defined. More indexes and their meanings are shown in Table 4.

a. *Consecutive days of negative SEP (CNS)*

The duration of precipitation deficit provides good information on drought. Consecutive days of negative SEP (CNS) shows this duration quantitatively.

TABLE 4. Characteristics of each index. The "i" is 365 or 15. The "j's" of each are CNS plus "i."

Name	Calculation	Simplified meaning
$ANES_i$	Accumulation of consecutive negative SEP	Shows the accumulated stress during drought.
CNS_i	Consecutive days of negative SEP	Shows how long precipitation has been in deficit.
PRN_j	(7), (8)	One day's precipitation needed for a return to normal conditions.
APD_j	(6)	Accumulated deficit of precipitation.
EDIj	(9), (10)	Standardized PRN_j.

b. *Accumulation of consecutive negative SEP (ANES)*

All positive SEPs are translated into zeroes of accumulation of CNS (ANES). Only consecutive negative SEPs are accumulated to make ANES. One benefit of the ANES is that drought duration is easily determined by the ANES because the absolute value of SEP is almost always less than 2.0.

c. *Accumulated precipitation deficit (APD_j)*

APD_j is calculated by a simple accumulation of precipitation deficit, as seen in (6):

$$APD_j = \sum_{N=1}^{j} P_N - AVG_j, \tag{6}$$

where j is DS, which is a different value from the dummy value of i. And AVG_j is the averaged daily precipitation of the date for many years during a predefined DS. The EP function in (2) or (3) is not used in APD. The APD is useful because the general public is more accustomed to simple precipitation accumulation than to the EP. And the APD is the best of all indexes when it is used for comparing drought damage in the same climatic conditions. But it is weak in representing drought intensity in a timely manner because it does not differentiate today's rainfall from yesterday's rainfall. If APD is calculated during the predefined dry duration instead of DS, it also can be an index that shows drought intensity.

d. *Precipitation needed for a return to normal (PRN_j)*

Negative values of DEP_j can be calculated directly into the 1-day precipitation needed for a return to normal condition (PRN_j) as follows:

$$PRN_j = DEP_j \Big/ \sum_{N=1}^{j} (1/N) \tag{7}$$

or

$$\mathrm{PRN}_j = \mathrm{DEP}_j \sum_{N=1}^{j} (N)/(ja), \qquad (8)$$

where "j" is same as in (6). Equation (7) is from (2) and (8) is from (3). For example, PRN_{400} shows the needed precipitation for recovery from the deficit accumulated during the last 400 days, in which daily depletion of water resources is taken into account. PRN_{365} is a little more important, because if PRN_{365} is positive, all other drought indexes are not calculated, in spite of accumulated water deficit.

e. Effective drought index (EDI_j)

Although CNS and ANES can be good information for assessing drought, APD and PRN are superior in showing drought intensity. But APD and PRN are dependent on background climatology, So we need another index like (9) for worldwide drought assessment:

$$\mathrm{EDI}_j = \mathrm{PRN}_j/\mathrm{ST}(\mathrm{PRN}_j) \quad \text{or}$$
$$\mathrm{EDI}_j = \mathrm{DEP}_j/\mathrm{ST}(\mathrm{DEP}_j), \qquad (9)$$

where $\mathrm{ST}[f(N)]$ denotes the standard deviation of $f(N)$ and j is DS. EDI is the most useful for worldwide application because it is independent of climatic characteristics of the locations. The values of (9), which originated from (2), are different from those that originated from (3).

f. Other indexes

Other indexes like those displayed in (10) can represent drought intensity also:

$$\mathrm{PNS}_{1j} = \mathrm{APD}_j/\mathrm{AVG}_j \quad \text{or}$$
$$\mathrm{PNS}_{2j} = \mathrm{PRN}_i/\mathrm{ST}[\mathrm{AVG}_j]. \qquad (10)$$

Equation (10) can be called as the percent normal as a second kind (PNS) because it is similar to the percent normal (Willeke et al. 1994) or deciles (Gibbs and Maher 1967), except that duration is defined by use of SEP. It is not difficult to understand that the EDI is superior to the PNS in showing drought intensity because the average (AVG) in (10) is not a product of the EP. All of these indexes are listed in Table 2.

5. Quantification of drought duration

For the better assessment, prediction, and mitigation of drought, the most scientifically quantified definition is needed. In this situation, by studying the concept of "severity," drought duration may be categorized as the consecutive days of EDI less than (-1.0). Also, by the concept of "long lasting," the duration of consecutive negative SEP values between drought periods has to be included in the drought duration. Using this definition, the onset, end, and duration of drought become clear.

6. Application to real data and discussion

a. Data quality checking

Initially, 37 yr (1960–96) of daily precipitation data for 193 stations of the High Plains region of the United States were chosen for the study. Most of the daily indexes explained before were calculated for each station during 36 yr (1961–96). Data quality was checked because of the amount of missing data during the period. Stations missing more than 1% of data were discarded. Then 113 stations remained. Next, missing data were changed to reflect the nearest (within 100 km) station's data. If no data were available within this area, a station's average value of calendar day was used.

b. Annual variations

Figures 2a–c show daily precipitation and drought indexes from 1 January 1995 until 31 December 1996. From day 250 in Fig. 2c, which is 7 September 1995 (232 in Fig. 2b) to 494 of 9 May 1996, EPs are smaller than MEPs. SEP translated these smaller EPs to long-lasting consecutive negative values. By these SEP, 245 (262) days of dry duration are detected and the largest value of DS (in abscissa) is detected as 610 (627) from the abscissa. An abrupt rising of EP and SEP on 9 May 1996 means a large rain event started on 8 May.

Major differences of Fig. 2b from Fig. 2c are shown in Table 5. Big differences in EDI, PRN, and onset day of drought are detected. These differences can be explained by the steeper curve of b compared to c in Fig. 1 and more sensitive variation of the EP curve to the precipitation amount in Fig. 2b than in Fig. 2c. It is important that the minimums of drought severity indexes appear at nearly the same date. No critical reasons verifying the superiority of (3) over (2) for practical use were found. But (2) has several merits. It can detect drought earlier and is more sensitive than (3).

By the use of a dummy DS of 15 instead of 365, the same kind of calculation is possible. It is called EP_s. Figures associated with EP_s (not shown) are not so simple as Fig. 2 because of the large seasonal fluctuation of EP. Heavy rains on 8, 9, and 10 May 1996 affect the indexes for only a brief period, and many negative values of SEP_s and DEP_s are detected during the year.

c. Interannual variations

Figure 3 shows each of the four indexes' 113-station average annual extreme minimums. Four indexes in both (2) and (3) are nearly in phase. This means that all of them can be used as drought indexes. Riebsame et al. (1991) figured that the drought of 1989 was the most severe one after 1961 in the High Plains. The same is recorded by USGS (1991). All indexes in Fig. 3 show a minimum value in 1989. This fact partly verifies that the indexes computed by EP function are good for practical use.

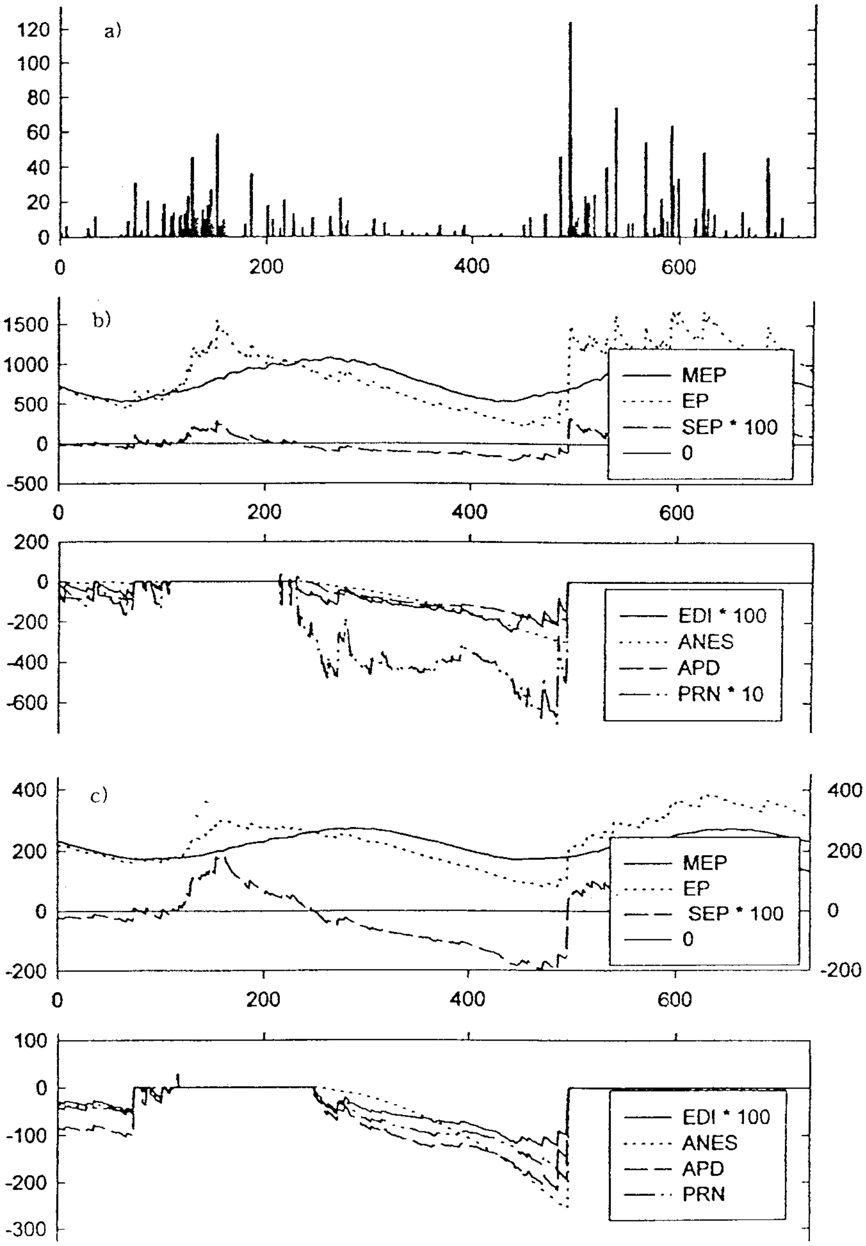

FIG. 2. Daily variations of (a) precipitation (unit is 1 mm), (b) EP series by Eq. (2), and (c) Eq. (3) at Hickman, Nebraska, USA, from 1 Jan 1995 to 31 Dec 1996. MEP is after a 5-day running mean. Abscissa axes reflect day-pass and ordinate axes index. Unit of index is mm (in APD and PRN) or day (in ANES) or dimensionless value (in all others).

TABLE 5. The differences of the results of (2) from those of (3).

	(2) Fig. 2b	(3) Fig. 2c
Dry duration	from 232 to 493	from 250 to 494
Drought duration	from 259 to 493	from 366 to 493
Minimum of CNS	−299.8 on day 493	−256.3 on day 494
Minimum of APD	−214.4 on day 484	−217.1 on day 484
Minimum of PRN	−70.5 on day 484	−173.4 on day 484
Minimum of EDI	−2.5 on day 469	−1.22 on day 469

d. Discussion

Table 5 shows that drought is detected successfully and quantitatively by a new technique. In spite of big differences in calculation, both (2) and (3) show good results. Although choosing one of the two or finding another equation for the best result is beyond the scope of this study, the results and physical meaning of the two should be considered briefly. Equation (2) reflects sensitivity but may exaggerate the situation, although

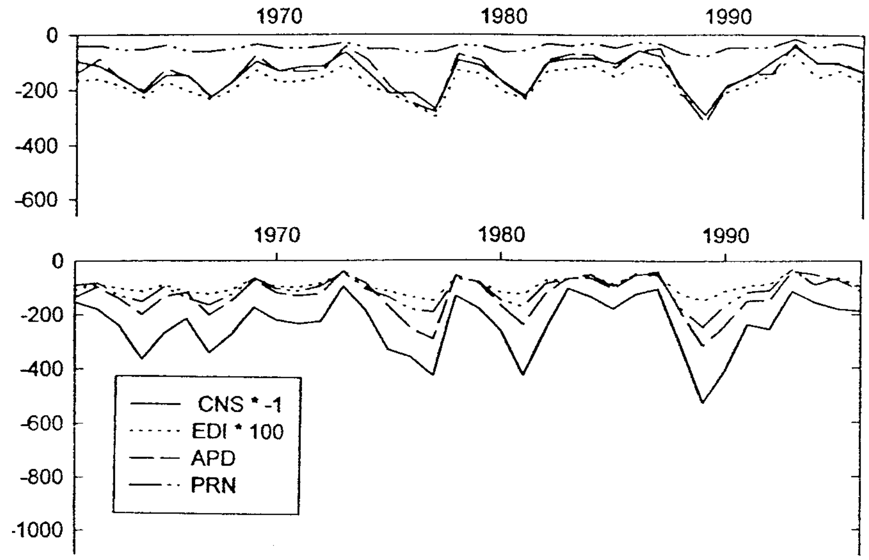

FIG. 3. Interannual variation of the mean of yearly minimum values for each drought index averaged through 113 stations in the High Plains region of the United States by (a) Eq. (2) and (b) Eq. (3). Unit of APD and PRN is 0.1 mm.

this exaggeration is positive for the early detection of disaster. Also, if this technique is applied to the upper basins of rivers, mountainous areas, or sandy areas or in detecting short-term drought like soil moisture, where runoff is so large in a few days after rainfall, it is better to use (2) than (3). Contrarily, if applied to lower basins of rivers, areas with good water retention, or long-term drought, (3) is superior to (2).

7. Summary and conclusions

Through comparative analysis, seven weaknesses of current drought indexes were discussed, and a new series of indexes was proposed to address these weaknesses. A new concept of EP, which is a series of daily quantities reproduced from random day's precipitation, was used for the solution. The MEP, DEP, and SEP after EP were used for detecting water deficit periods. After the detected water deficit period, the CNS, ANES, PRN, APD, PNS, and EDI were calculated as main indexes that can assess drought severity. The benefits and weaknesses of each index were discussed. It is also proposed that two kinds of timescales of drought be used to detect both long-lasting drought (lack of reservoir water) and short-term drought (lack of soil moisture). A new quantified definition of drought duration was also made.

Applications using real data and comparisons with other current indexes were also carried out over the High Plains region in the United States. It was found that all of the new indexes were good enough to show the drought intensity. The EDI was the best index in assessing drought severity worldwide and the PRN was the best suited for limited areas in a timely manner.

In this study, new techniques were used only to assess the water deficit, but these techniques can be applied to assess water surplus also. Disasters associated with lack of or surplus water resources can be assessed, monitored, and predicted more objectively and quantatively and can be mitigated effectively by using these new techniques.

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