



Drought characterization [Part 1. Components of drought planning. 1.3. Methodological component]

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Chapter 7. Drought characterization

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SUMMARY – Drought indices have been devised for identification of drought and characterization of its severity. Using drought indices, the duration, intensity and areal extent for each drought episode can be defined. They can be used to describe all types of droughts (that is meteorological drought, hydrological drought, agricultural droughts and socioeconomic drought). According to the type of drought, the appropriate drought index is selected. Drought indices are composite numerical figures incorporating mainly values of hydrometeorological indicators. The most popular drought indices presented in the report and applied in the participating countries in the MEDROPLAN project include the SPI, the PDSI, the method of Deciles, the recently developed RDI and others. Crucial elements in the procedure for calculating drought severity by using drought indices are the time step adopted and the threshold of each index selected. During the project a common methodology for applying drought indices for monitoring and assessment of droughts and estimation of drought risk was devised and applied to all case studies.

Key words: Drought indices, frequency, duration, intensity, areal extent, type of drought.

Introduction

Drought is one of the major water related hazards. However, there is no universally accepted definition of drought. Perhaps the most general definition is the one which considers drought as a significant decrease of water availability during a long period of time and over a large area. This implies that drought should be considered as a three dimensional event characterized by its severity, duration and affected area.

Various methodologies have been proposed for identification, quantification and monitoring of drought phenomena. Among them, the most popular seem to be single factors known as *drought indices*, which are special combinations of indicators comprising meteorological, hydrological and other data.

Drought indices are important and useful elements for drought monitoring and assessment since they simplify complex interrelationships between many climate and climate-related parameters. Indices make it easier to communicate information about climate anomalies to diverse user audiences and allow scientists to assess quantitatively climate anomalies in terms of their intensity, duration, spatial extent and frequency. This allows the analysis of the historical droughts events and their recurrence probability.

It should be mentioned that drought indices may be grouped in two categories, the general indices and the specific indices. The general indices give an overview of the drought occurrence and its severity, whereas the specific indices are mostly useful for correlating drought events to the anticipated damages from drought in the various sectors of the economy, the environment and the society. This chapter gives emphasis on the general drought indices, which are analytically presented. Namely, the general indices, which were selected for application for Mediterranean countries, are the Deciles, the Standardized Precipitation Index (SPI), the Palmer Index, as well as the new Reconnaissance Drought Index (RDI). Apart from these general indices, references are also made to specific indices for the purpose of a systematic presentation.

Very important aspects, when drought indices are used, are the thresholds representing the levels of drought severity. It is needless to say that these thresholds should be associated with the anticipated damages corresponding to each level of severity.

Drought indices are employed to characterize drought and its statistical properties. Drought analysis from a stochastic point of view provide information required for the subsequent risk analysis (probabilities of drought occurrence and drought impacts).

Drought indices provide spatial and temporal representations of historical droughts and therefore place current conditions in historical perspective. They are valuable for providing decision makers with a measurement of the abnormality of recent weather for a region.

Drought management depends on indices to detect drought conditions, and thresholds to activate drought responses. Indices and thresholds are important to detect the onset of drought conditions, to monitor and measure drought events, and to reduce drought impacts.

Several drought indices are proposed and used to characterize drought and analysing observed data after fixing a threshold and a time scale.

Drought identification and characterization in a given region permit in performing water resources planning and management of their rational uses especially in the arid and semi-arid zones. For the operational management however monitoring and early warning systems base on certain indices should be developed.

Overview of drought indices

Drought-trigger indices include meteorological and hydrological drought indices. Meteorological drought indices respond to weather conditions that have been abnormally dry or abnormally wet. When conditions change from dry to normal or wet, for example, the drought measured by these indices ends without taking into account streamflow, lake and reservoir levels, and other longer-term hydrologic impacts. Meteorological drought indices do not take into account human impacts on the water balance, such as irrigation. Hydrological drought indices take into account water management and streamflow, lake and reservoir levels, and other longer-term hydrologic impacts.

Drought-trigger indices assess drought conditions in a specific time. However, it is necessary to define a drought threshold value for each one of the drought indices. This threshold distinguishes a drought category and determines when drought responses should begin and end.

A single indicator is useful for drought monitoring but is not well suited when the purpose is to identify and characterize historical droughts either at a site or at regional scale.

A method to characterize drought based on drought-trigger indices should:

- (i) Provide criteria for declaring the beginning and the end to a drought.
- (ii) Represent the concept drought in a particular region.
- (iii) Correlate to quantitative drought impacts (via drought-responses indicators) over different geographical and temporal time scales.

Due to the complexity of drought, approaches to develop drought indices and triggers are needed (Steinemann, 2003). Because drought conditions depends on numerous factors, such as water supplies and demands, hydrologic and political boundaries and antecedent conditions indices should be sensitive to the contexts. But indices often lack spatial and temporal transferability, comparability among scale, and relevance to critical drought impacts. Thresholds often lack statistical integrity, consistency among drought categories, and correspondence with desired management goals (Steinemann, 2003). In many cases multiple indices are used but multiple indices on multiple scales can confound the complexity of single indices. Consequently it is necessary the implementation of drought identifications methods.

The parameters to be characterized for drought identification are the following:

- (i) Frequency. Analyse the long-term averages in terms of rainfall to determine how many droughts occur within 10 years.

(ii) Timing.

(iii) Rate of onset.

(iv) Intensity. Intensity of the drought: ratio between cumulated deficit and duration. Drought intensity is a measure of rainfall deficiency over three months (or other index). Determine a threshold of rainfall that can be correlated with the intensity. For example, for a particular region, between 5 and 10% above the lowest on record is rated as serious and less than 5% above lowest on record is rated as severe.

(v) Cumulated deficit: Sum of the negative deviation throughout the drought duration.

(vi) Duration. Number of consecutive intervals where the variable is below the threshold. Occasionally, droughts last for 7 or 8 years, but within that period the severity may fluctuate with spells of rainfall, although still well below average. Other droughts are shorter (one or two years) but more intense with very little rain recorded.

(vii) Spatial extent. It is unlikely that an entire country could suffer drought at the same time. Some droughts can be localised with other relatively close areas receiving normal rainfall.

(viii) Predictability.

One of the options to provide an approach for expressing indices within a probabilistic framework and for evaluating their stochastic properties is to use a multistage homogeneous Markov model. This method developed by Steinemann (2003) offers an equitable basis for evaluation, ease of interpretations and direct application to water management decisions. The model based on Markov methodology is applied to describe and interpret the indices in terms of their transitioning, persistence, duration and frequency between categories. The model can provide quantitative results and the criteria for what is desirable in indices and triggers, such as degree of persistence, depends on the decision making context.

The run method allows an objective at site and regional drought identification and characterization, and therefore it represents a methodology for an analysis oriented to define best drought mitigation alternatives. The run method is based on the relationship between drought and negative runs in rainfall time series considering a hydrological variable and a critical threshold level (Yevjevich, 1967; Rossi *et al.*, 2003).

Assessment of drought impacts is difficult due to the interaction of several components within the system which is affected by drought. Feedback or indirect effects might be sometimes greater than direct (first order) effects. First order interactions occur between physical components and biological components (impacts on agriculture and environment) or socio-economic components. Second order interactions occur between biological and socio-economic components. Also feedback effects from biological and socio-economic components can modify the status of some physical components of the system. Finally the third order interactions occur between institutions and policy makers with the functioning of the system.

Drought-trigger indices assess drought conditions in a specific time. However, it is necessary to define a drought threshold value for each one of the drought indices. This threshold distinguishes a drought category and determines when drought responses should begin and end.

Table 1 summarizes the most commonly used drought indices, whereas the methods of calculation are outlined in the following section. A complete analysis of drought indices is provided by Hayes (2004).

Table 1. Summary of the main drought indices

Index	Description and Use	Strengths	Weaknesses
Meteorological Drought Indices			
Percent of Normal Precipitation and Accumulated Precipitation Departure	Simple calculation Used by general audiences	Effective for comparing a single region or season	Precipitation does not have a normal distribution Values depend on location and season
Deciles Gibbs and Maher (1967)	Simple calculation grouping precipitation into deciles Used by the Australian Drought Watch System	Accurate statistical measurement Simple calculation Provides uniformity in drought classifications	Accurate calculations require a long climatic data record
Standardized Precipitation Index (SPI) McKee <i>et al.</i> (1993)	Based on the probability of precipitation for any time scale. Used by many drought planners	Computed for different time scales, provides early warning of drought and help assess drought severity	Values based on preliminary data may change Precipitation is the only parameter used
Palmer Drought Severity Index (PDSI) Palmer (1965) Alley (1984)	Soil moisture algorithm calibrated for relatively homogeneous regions Used in the USA to trigger drought relief programs and contingency plans	The first comprehensive drought index, used widely Very effective for agricultural drought since includes soil moisture	PDSI may lag emerging droughts. Less well suited for mountainous areas of frequent climatic extremes Complex Categories not necessarily consistent, in terms of probability of occurrence, spatially or temporally
Crop Moisture Index (CMI) Palmer (1968)	Derivative of the PDSI Reflects moisture supply in the short term	Identifies potential agricultural droughts	It is not a good long-term drought monitoring tool
Recoissance Drought Index (RDI) Tsakiris (2004)	Similar to SPI Basic variable P/PET	Drought is based on both precipitation and potential evapotranspiration Appropriate for climate change scenarios	Data needed for calculation of PET
Hydrological Drought Indices			
Palmer Hydrological Drought Index (PHDI) Palmer (1965)	Same as PDSI but more exigent to consider a drought end. The drought terminates only when the ratio of Pe (moisture received to moisture required) is 1	Same as PDSI	Same as PDSI
Surface Water Supply Index (SWSI) Shafer and Dezman (1982)	Developed from the Palmer Index to take into account the mountain snowpack	Represents surface water supply conditions and includes water management Simple calculation Combines hydrological and climatic features. Considers reservoir storage	Management dependent and unique to each basin, which limits inter-basin comparisons Does not represent well extreme events

Basic notions to apply the drought indices

Once a set of general drought indices has been selected, several basic assumptions will make their use effective and easy to interpret. A similar procedure has been selected for the Drought Monitoring System proposed for USA.

Normal Conditions

Since drought has been postulated as the deficient deviation from the normal conditions, it is necessary to clarify what is meant by *normal conditions*. Some researchers use a general level, which

corresponds to water balance between water availability and consumption; most of the researchers however use the mean figures of meteorological parameters to establish the normal conditions. If for instance the precipitation is the key parameter to measure annual drought, the arithmetic mean of annual precipitation for a number of years is the level taken as the basis for calculating the deviations.

From results of various studies, it can be inferred that the *median* instead of the arithmetic mean can represent more reliably the normal conditions in an area. This is mainly because extreme values of fatal outliers do not influence the median as they influence the arithmetic mean. The same happens when new data are added to the existing series of data.

As a concluding remark, it can be concluded that, in some cases, the arithmetic mean could be replaced by the median for establishing the normal conditions.

Time step and reference period

The data required for drought assessment are usually monthly data. No smaller time step has any significant effect when drought is assessed by general indices. Only in some very specialized indices related to crucial water deficit aspects, a smaller time step can be used.

Therefore, for the purpose of establishing drought-meteorological networks, monthly values of the key meteorological/hydrological parameters are required.

Further regarding the reference period of drought assessment it seems logical to consider longer period of time. If short reference period is selected, many complications will be encountered related to carry-over quantity of water from period to period. Furthermore, lag time in hydrological processes makes any kind of drought assessment unreliable if a short period of time is adopted.

Based on these thoughts, the task of assessing droughts using general indices can be more efficiently implemented if the reference period is an entire season or an entire year. A hydrological year starts the first day of October and ends at the end of September of the next year for the Mediterranean Countries. By fixing the reference period, the dimension of duration could be neglected.

Spatial integration

It is generally accepted that drought is a regional phenomenon. However, meteorological information is collected at selected stations, which can be considered as representing the area attributed to them (e.g. by Thiessen polygons). The spatial integration is based on these areas/polygons. Polygons under drought are aggregated to estimate the total critical area which is affected by drought.

However, this approach disregards the hydrological processes, which are based on the hydrological basin scale. As known, the hydrological basin is the unit for any water resources management scheme according to the natural laws. This primary principle is the cornerstone of the new Water Framework Directive of the European Union. For the small basins in particular, it is even more obvious that drought should use the whole basin as the unit since no significant variability over the area of the basin is expected.

Therefore it could be proposed that drought analysis could be applied to the basin or subbasin as the unit; after transferring the data from the existing stations on the average basin scale. There might be cases in which one station can represent an entire basin or sub-basin and in this case, calculations for drought indices can be performed directly.

In case of assessment of drought at a basin scale the "interpolate – calculate" method could also be used. By this method, all principal data (e.g. precipitation, temperature, etc) are transferred to the squares in which the basin is divided upon. Then, the weighted average is used to calculate the representative meteorological data of the entire basin and then the drought indices are calculated. The opposite procedure by which the drought indices are calculated at the locations of the meteorological stations and then they are transferred to the basin scale should be avoided mainly due to the "non-linearity" problems related to the procedure.

The above approach seems to give significant opportunities for relating meteorological drought to hydrological drought and also it will lead to a more efficient linkage between meteorological drought indices and the anticipated damage in the various sectors of the economy.

Apart from the suggested approach above, in a number of cases (e.g. very big river basins) it could be also possible to base severity indices on the data derived directly from the meteorological stations themselves. By this way we could construct isolines of the selected indices, which show the spatial variability of the drought severity.

Spatial interpolation of meteorological data

As known, the most important parameter considered in the evaluation of meteorological drought indices is precipitation. There are many available methods, which can be used for spatial interpolation of precipitation. Thiessen polygons may be used to transfer the data at the basin scale directly. The weighted average is calculated and then corrected for the deviation in the altitude.

Another popular way to transfer precipitation data from the stations to the basin level is through the mediation of squares, which the basin is divided in.

Therefore, from the stations the data are transferred to the squares and from the squares to the entire basin. In the latter case, several techniques could be used. Among the most popular are the kriging, the splines, the inverse of square distance weighting, the trend surface and the multiple linear regression.

Similar techniques can be used for transferring other meteorological data at the basin level.

Selected drought indices

Deciles

A simple meteorological index is the rainfall deciles, in which the precipitation totals for the preceding three months are ranked against climatologic records. If the sum falls within the lowest decile of the historical distribution of 3-month totals, then the region is considered to be under drought conditions (Kinmonth *et al.*, 2000). The drought ends when: (i) the precipitation measured during the past month already places the 3-month total in or above the fourth decile, or (ii) the precipitation total for the past three months is in or above the eighth decile.

The first decile is the precipitation amount not exceeded by the lowest 10% of the precipitation occurrences. The second decile is the precipitation amount not exceeded by the lowest 20% of occurrences. These deciles continue until the rainfall amount identified by the tenth decile is the largest precipitation amount within the long-term record. By definition, the fifth decile is the median, and it is the precipitation amount not exceeded by 50% of the occurrences over the period of record. The deciles are grouped into five classifications.

Table 2 presents the classification of drought conditions according to deciles.

Table 2. Classification of drought conditions according to deciles

Decile Classifications	
deciles 1-2: lowest 20%	much below normal
deciles 3-4: next lowest 20%	below normal
deciles 5-6: middle 20%	near normal
deciles 7-8: next highest 20%	above normal
deciles 9-10: highest 20%	much above normal

The advantage of the decile approach is its computational ease, but its 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 usually falls, can activate the first stopping rule, even though the amount of precipitation is trivial and does not terminate the water deficit. A supplemental third rule, that considers the total precipitation since the beginning of drought, may be used (Keyantash and Dracup, 2002). According to this rule, if the total precipitation exceeds the first decile for all drought months, then the meteorological drought may be considered terminated.

Standardized Precipitation Index

The Standardized Precipitation Index (SPI) was developed for the purpose of defining and monitoring drought (McKee *et al.*, 1993).

The SPI calculation for any location is based on a series of accumulated precipitation for a fixed time scale of interest (i.e. 1, 3, 6, 9, 12,... months). Such a series is fitted to a probability distribution, which is then transformed into a normal distribution so that the mean SPI for the location and desired period is zero (Edwards and McKee, 1997). Positive SPI values indicate greater than median precipitation, and negative values indicate less than median precipitation. Because the SPI is normalized, wetter and drier climates can be represented in the same way, and wet periods can also be monitored using the SPI.

Thom (1958) found the gamma distribution to fit well climatological precipitation time series. The gamma distribution is defined by its probability density function:

$$g(x) = \frac{1}{\beta^\alpha \Gamma(\alpha)} x^{\alpha-1} e^{-x/\beta} \quad \text{for } x > 0 \quad (1)$$

where: α , β are the shape and scale parameters respectively, x is the precipitation amount and $\Gamma(\alpha)$ is the gamma function. Computation of the SPI involves fitting a gamma probability distribution to a given frequency distribution of precipitation totals for a station. The alpha and beta parameters of the gamma probability density function are estimated for each station, for each time scale of interest (1, 3, 6, 9, 12 months, etc.), and for each month of the year. Maximum likelihood solutions are used to optimally estimate α and β :

$$\begin{aligned} \alpha &= \frac{1}{4A} \left(1 + \sqrt{1 + \frac{4A}{3}} \right) \\ \beta &= \frac{\bar{x}}{\alpha} \end{aligned} \quad (2)$$

where $A = \ln(\bar{x}) - \frac{\sum \ln(x)}{n}$, and n = number of observations

The resulting parameters are then used to find the cumulative probability of an observed precipitation event for the given month and time scale for the station in question. Since the gamma function is undefined for $x = 0$ and a precipitation distribution may contain zeros, the cumulative probability $H(x)$ is calculated by the equation:

$$H(x) = q + (1 - q) G(x), \quad (3)$$

where q is the probability of a zero and $G(x)$ the cumulative probability of the incomplete gamma function. If m is the number of zeros in a precipitation time series, then q can be estimated by m/n . The cumulative probability is then transformed to the standard normal random variable z with mean zero and variance one, which is the value of the SPI. Once standardized the strength of the anomaly is classified as set out in Table 3. This table also contains the corresponding probabilities of occurrence of each severity arising naturally from the normal probability density function. Thus, at a given location for an individual month, moderate droughts ($SPI \leq -1$) have an occurrence probability of 15.9%, whereas extreme droughts ($SPI \leq -2$) have an event probability of 2.3%. Extreme values in the SPI will occur, by definition, with the same frequency at all locations.

Table 3. Drought classification by SPI value and corresponding event probabilities

SPI value	Category	Probability (%)
2.00 or more	Extremely wet	2.3
1.50 to 1.99	Severely wet	4.4
1.00 to 1.49	Moderately wet	9.2
0 to 0.99	Mildly wet	34.1
0 to -0.99	Mild drought	34.1
-1.00 to -1.49	Moderate drought	9.2
-1.50 to -1.99	Severe drought	4.4
-2 or less	Extreme drought	2.3

The SPI can track drought on multiple time-scales. The U.S. National Drought Mitigation Center (NDMC) computes the SPI with five running time intervals, i.e. 1-, 3-, 6-, 9-, and 12-months, but the index is flexible with respect to the period chosen. This powerful feature can provide an overwhelming amount of information unless researchers have a clear idea of the desired intervals. Moreover, being a standardized index, the SPI is particularly suited to compare drought conditions among different time periods and regions with different climatic conditions.

A program to calculate SPI proposed by the National Drought Mitigation Center can be obtained from:

http://www.drought.unl.edu/monitor/spi/program/spi_program.htm

The method of calculation includes the following steps:

- (i) Data preparation. Computation of a time series of accumulated precipitation value for a fixed time scale. At least 30 years of data are highly recommended.
- (ii) Determination of a probability frequency distribution that statistically fits the time series of precipitation data.
- (iii) Calculation of the non-exceedence probabilities related to the accumulated values.
- (iv) Derivation of the corresponding normal standard quantiles, which represent the SPI values.

Palmer Drought Severity Index (PDSI)

The PDSI was introduced by Palmer (1965) for the assessment of the meteorological drought. PDSI is referred to as an index of meteorological drought, however, the procedure considers precipitation, evapotranspiration, and soil moisture conditions, which are determinants of hydrological drought, i.e. the period during which the actual water supply is less than the minimum water supply necessary for normal operations in a particular region. The basic concepts and steps for computing the PDSI are presented below.

Step 1: Hydrological Accounting

The computation of the PDSI begins with a climatic water balance using long series of monthly precipitation and temperature records as inputs. The soil is divided into two layers, where the upper layer, called surface soil, contains 25 mm of available moisture at field capacity. This is the layer onto which the rain falls, and from which evaporation takes place. Evaporation loss from the surface layer, L_S , is assumed to take place at the potential rate which is estimated by the Thornthwaite method. Moisture cannot be removed from, or recharged to, the underlying layer until the surface layer has been depleted or saturated. The loss from the underlying layer, L_U , depends on the moisture content, computed Potential Evaporation (PE), and available water capacity (AWC) of the soil system. If $PE > P$, then

$$L_S = \min [S_{S_u} (PE - P)], \quad (4)$$

$$L_U = [(PE - P) - LS] S_U / AWC, \quad L_u < S_U, \quad (5)$$

where S_S and S_U are the amounts of available moisture stored at the beginning of the month in the surface and the underlying layers, respectively. Runoff is assumed to occur, if and only if, both layers are at moisture capacity, AWC.

In addition to PE, three more potential terms are used and they are defined as follows: Potential Recharge (PR) is the amount of moisture required to bring the soil to its water holding capacity given by:

$$PR = AWC - (S_S + S_U) \quad (6)$$

Potential loss (PL) is the amount of moisture that could be lost from the soil by evapotranspiration during a zero precipitation period given by:

$$PL = PL_S + PL_U \quad (7)$$

where

$$PL_S = \min [PE, S_S] \quad (8)$$

$$PL_U = [PE - PL_S] S_U / AWC, PL_U < S_U \quad (9)$$

The Potential Runoff (PRO) is defined as the difference between the potential precipitation and the potential recharge. Potential precipitation is equal to AWC, hence, PRO is given by:

$$PRO = AWC - PR = S_S + S_U \quad (10)$$

Step 2: Climatic Coefficients

A calibration of the water balance model to normal levels is accomplished by simulating the water balance over the period of available historical records of temperature and precipitation and so deriving the moisture capacity of the lower soil layer and four coefficients for the study area. The following four monthly coefficients are computed using the four potential terms, PE, PR, PRO and PL:

$$a_j = \frac{\overline{ET}_j}{\overline{PE}_j} \quad (11)$$

$$b_j = \frac{\overline{R}_j}{\overline{PR}_j} \quad (12)$$

$$c_j = \frac{\overline{RO}_j}{\overline{PRO}_j} \quad (13)$$

$$d_j = \frac{\overline{L}_j}{\overline{PL}_j} \quad (14)$$

where ET is the evapotranspiration, R is the soil water recharge, RO is the runoff, and L is the total water loss from the soil. The over-bars indicate the average values from the historical records for each month j.

Step 3: CAFEC Values

The derived coefficients are used to reanalyse the time series, in order to determine the amount of moisture required for "normal" weather during individual months. In particular, the Climatically Appropriate For Existing Conditions (CAFEC) values are computed, and they are denoted by a circumflex (^). For example, the CAFEC value for ET_j for month j is:

$$\hat{ET}_j = a_j \cdot PE_j \quad (15)$$

where PE_j is the potential evapotranspiration for the current month j. Hence, the CAFEC precipitation value, P , is computing as:

$$P = a_j \cdot PE + b_j \cdot PR + c_j \cdot PRO - d_j \cdot PL \quad (16)$$

Step 4: Moisture Anomaly Index

For each month j , the difference between the actual precipitation and the CAFEC precipitation is an indicator of the water deficiency or surplus for that month at the station or area under study.

This is expressed as $D = P - \hat{P}$. These departures (D) are converted into moisture anomaly (Z) indices, known as Palmer Z-index, according to:

$$Z = K_j \cdot D \quad (17)$$

where K_j is a weighting factor for the month j , which takes into account the spatial variability of departures D , such that they are independent of time and space.

Step 5: Drought Severity

In this final step the Z-index time series is analyzed to develop criteria for the beginning and ending the periods of drought and a formula for determining drought severity. Palmer's methodology involves computing, for each month, three intermediate indices X_1 , X_2 , and X_3 and a probability factor. Palmer expressed the beginning and the termination of drought (or wet period) in terms of the probability that the dry or wet spell has started or ended. A drought or wet spell is definitely over when this probability reaches or exceeds 100%, but the drought or wet spell is considered to have ended the first month when the probability became greater than 0% and then continued to remain above 0% until it reached 100%. During the period of "uncertainty" when an existing drought (or wet period) may or may not be over (i.e. when the probability is between 0% and 100%), the model computes the three intermediate indices X_1 , X_2 , and X_3 . X_1 is the index value for an incipient wet spell, X_2 is the index value for an incipient drought, and X_3 is the index value for an established drought event or wet spell. All three intermediate indices are calculated using the following empirical expression:

$$X_j = 0.897 \cdot X_{j-1} + \frac{Z_j}{3} \quad (18)$$

where Z_j represents the value of the moisture anomaly index or Z-index for the month j . The Palmer's model selects the value of one of the intermediate indices and assigns to PDSI depending on the value of probability factor. For example, if the probability factor takes a value between 0 and 1, then PDSI takes the value of X_1 , if the probability factor takes a value between 0 and -1, then PDSI takes the value of X_2 and when the probability factor takes values larger than 1 or smaller than -1 then PDSI takes the value of X_3 . The X_3 term responds much slower than PDSI to soil moisture changes and is an index for the long-term hydrologic moisture conditions known as Palmer Hydrological Drought Index (PHDI). The classification of weather based on PDSI, PHDI, and Z-Index (Palmer, 1965) is shown in Table 4. It should be noted that the Z-Index provides an indication of the persistence of the drought phenomenon, whereas PDSI denotes the drought severity.

Table 4. Classification of weather using PDSI, PHDI, and Z-index (Palmer, 1965).

PDSI, PHDI, Z-index	Weather
> 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 -0.99	Moderate drought
-3.00 to -3.99	Severe drought
< -4.00	Extreme drought

The Palmer method used for calculating the PDSI, PHDI, and Z-Index has a number of limitations and deficiencies (Alley, 1984). The limitations of the method can be classified into two categories: the water balance model deficiencies and the PDSI characteristics. The first category of limitations of the Palmer method includes:

- (i) The use of the Thornthwaite method for the estimation of the potential evapotranspiration although other methods could be employed. However, with the limited available data required by the Palmer method, only a simple methodology for the estimation of the potential evapotranspiration, such as the Thornthwaite method, should be used.
- (ii) The arbitrary amount of 25 mm of the moisture capacity of the surface soil layer. The soil moisture capacity could be widely changed depending on the climate, the soil texture, and the vegetation coverage of the area.
- (iii) The assumption that the runoff is estimated without any lag in the time distribution. Thornthwaite and Mather (1955) and Mather (1981) suggested that 50%-75% of the runoff should be delayed each month in order to reproduce monthly flow volumes observed in streams. The fraction of runoff delayed varies considerably depending on the depth and texture of the soil, the physiography and size of the basin, and the nature of the groundwater system.
- (iv) The "threshold-type" model of the Palmer method in that it assumes that runoff does not occur until the moisture capacity of the upper and lower soil layer is filled. This assumption tends to underestimate the recharge during the summer and early autumn months.
- (v) No allowance is given for the effect of snowmelt or frozen ground but this is not a problem in the Mediterranean climatic region where snowfall occurs only at high elevations.

The limitations of the PDSI characteristics can be summarized as:

- (vi) The arbitrary definition of PDSI classes. These classes have been defined from data from central Iowa and Kansas.
- (vii) The sensitivity of PDSI values to K_j factors (Equation 17). But the overall duration of droughts of various magnitudes is relatively insensitive to K_j variations.
- (viii) The sensitivity of PDSI values to the climate of the calibration period.

Despite several assumptions used in the water balance calculations, other limitations and deficiencies, and the empirical nature of some of the standardized coefficients, the PDSI can be a useful tool for both research and operational drought assessment, if used appropriately and acknowledged its limitations stated above (Karl *et al.*, 1987; Rao and Voeller, 1997). It should also be mentioned that the Palmer method tackles the difficult problem of droughts using only monthly data of precipitation and temperature.

A program to calculate PDSI is available (previous registration) at:

<http://nadss.unl.edu/downloads/>

Reconnaissance Drought Index (RDI)

A new reconnaissance drought identification and assessment index was first presented in the coordinating meeting of MEDROPLAN project in March 2004 (Tsakiris, 2004), while a more comprehensive description was presented in Tsakiris *et al.* (2006).

The index, which is referred to as the Reconnaissance Drought Index, RDI, may be calculated by the following equations. For illustrative purposes the yearly expressions are presented first. The first expression, the initial value (α_0), is presented in an aggregated form using a monthly time step and may be calculated for each month of the hydrological year or a complete year. The α_0 is usually calculated for the year i in an annual basis as follows:

$$\alpha_o^{(i)} = \frac{\sum_{j=1}^{12} P_{ij}}{\sum_{j=1}^{12} PET_{ij}} , i = 1 \text{ to } N, \text{ and } j = 1 \text{ to } 12 \quad (19)$$

in which P_{ij} and PET_{ij} are the precipitation and potential evapotranspiration of the month j of the year i , starting usually from October as it is customary for Mediterranean countries and N is the total number of years of the available data.

A second expression, the Normalised RDI, ($RDIn$) is computed using the following equation for each year, in which it is evident that the parameter $\bar{\alpha}_o$ is the arithmetic mean of α_o values calculated for the N years of data.

$$RDIn^{(i)} = \frac{\alpha_o^{(i)}}{\bar{\alpha}_o} - 1 \quad (20)$$

The third expression, the Standardised RDI (RDI_{st}), is computed following a similar procedure to the one that is used for the calculation of the SPI. The expression for the Standardised RDI is:

$$RDI_{st}^{(i)} = \frac{y^{(i)} - \bar{y}}{\hat{\sigma}_y} \quad (21)$$

in which y_i is the $\ln(\alpha_0^{(i)})$, \bar{y} is its arithmetic mean and $\hat{\sigma}_y$ is its standard deviation.

It is noted that the above expression is based on the assumption that the α_o values follow a lognormal distribution. The Standardised RDI behaves in a similar manner as the SPI and so is the interpretation of results. Therefore, the RDI_{st} can be compared to the same thresholds as the SPI.

The choice of the lognormal distribution is not constraining but it assists in devising a unique procedure instead of various procedures depending on the probability distribution function which best fits the data. However, the hypothesis that the data of the $RDIn$ follow a lognormal distribution seems to be the most appropriate. In all examples analyzed during the establishment of the RDI, the goodness-of-fit tests confirmed that the lognormal distribution fits the data satisfactorily.

It should be emphasised that the RDI is based on both precipitation and potential evapotranspiration. The mean initial index ($\bar{\alpha}_o$) represents the normal climatic conditions of the area and is equal to the well known Aridity Index as was proposed by the FAO.

Among others, some of the advantages of the RDI are:

- (i) It is physically sound, since it calculates the aggregated deficit between precipitation and the evaporative demand of the atmosphere.
- (ii) It can be calculated for any period of time (e.g. 1 month, 2 months etc).
- (iii) The calculation always leads to a meaningful figure.
- (iv) It can be effectively associated with agricultural drought.
- (v) It is directly linked to the climatic conditions of the region, since for the yearly value it can be compared with the FAO Aridity Index.
- (vi) It can be used under "climate instability" conditions, for examining the significance of various changes of climatic factors related to water scarcity.

From the above advantages, it can be concluded that the RDI is an ideal index for the reconnaissance assessment of drought severity for general use giving comparable results within a large geographical area, such as the Mediterranean region.

It should be mentioned that usually droughts in the Mediterranean are accompanied by high temperatures, which lead to higher evapotranspiration rates. Evidence for this has been produced from

simultaneous monthly data of precipitation and evapotranspiration in many Greek watersheds. From the cases analyzed it seems that about 90% of them comply with the previous statement. (Tsakiris and Vangelis, 2005) Therefore, the RDI is expected to be more sensitive index than those related only to precipitation, such as the SPI. A graph comparing the annual figures of SPI and RDI is presented in Fig. 1.

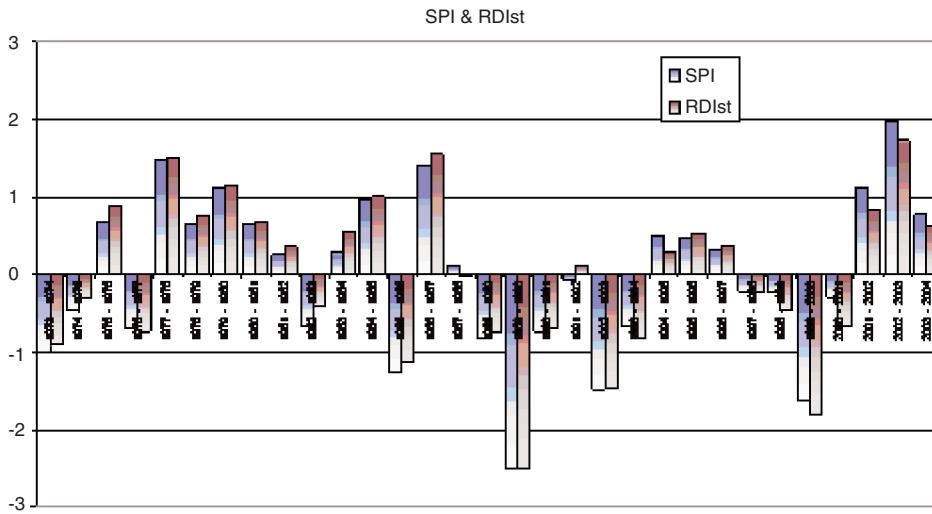


Fig. 1. Annual SPI and RDI for a series of hydrological years (Oct-Sep) (1973-2004).

The RDI can be calculated for any period of time from one month to the entire year, even starting from a month different than October, which is customary for the Mediterranean. Very significant results can be derived if the period of analysis coincides with the growing season of the main crops of the area under study or other periods related to sensitive stages of crop growth. Then, the RDI can be associated successfully with the expected loss in rainfed crop production, which in turn is linked to the anticipated damages in the agricultural sector due to drought occurrence.

As it was shown from previous studies, precipitation (and therefore SPI) was not successfully correlated to agricultural production (Tsakiris and Vangelis, 2005). However, the inclusion of potential evapotranspiration (PET) in the calculation of the RDI enhances its validity in studies aiming at risk assessment in agriculture caused by drought occurrence.

Other Drought Indices

Apart from the general indices that were presented so far for future use, it is also worth presenting concisely some specific indices that are quite widely used. These indices are used for agricultural, economic, industrial, tourist and recreational uses.

The **Bhalme-Mooley Drought Index (BMDI)** (Bhalme and Mooley, 1980) provides a good measure of the current status of drought that is the effect of short periods of dry weather, unlike the PDSI which is designed to evaluate the degree of severity and frequency of prolonged periods of abnormally dry conditions. BMDI is simple and less complex than other indices because it is not involving terms such evapotranspiration or soil water capacity, which are parameters especially difficult to estimate and it is based only in monthly precipitation.

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

$$RAI = \pm 3 \frac{P - \bar{P}}{\bar{E} - \bar{P}} \quad (22)$$

where P is measured precipitation, \bar{P} is average precipitation, and \bar{E} is average of 10 extrema. For positive anomalies, the prefix is positive and \bar{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. Oladipo (1985) found that differences between the RAI and the more complicated indices of Palmer and Bhalme-Mooley were negligible.

A traditional assessment of hydrological drought is the **Total Water Deficit**, which is synonymous with drought severity S. This severity is the product of the duration D, during which observed flows are consistently below some truncation level, and magnitude M, which is the average departure of streamflow from the truncation level during the drought period (Dracup *et al.*, 1980). The truncation level or flow threshold might be chosen in a number of ways and the choice is amongst others a function of the type of water deficit to be studied. It is possible to apply a percentage of the mean flow (Dracup *et al.*, 1980), other low flow indices (e.g. mean annual n-day flow), or a percentile from the flow duration curve (usually the 90th percentile flow or Q90). The threshold might be fixed or vary over the year in a monthly or seasonal pattern (Demuth and Stahl, 2001). The total water deficit can be applied to various time scales of streamflow data, from daily to annual time series. Since this approach consists of the application of run method to streamflow it might be considered as another index.

This method basically coincides with the run method, which can be also applied to streamflow. The Run Method is presented in this text in the section of spatial extent of drought as a method for determining the areal extent of drought.

The **Palmer Hydrological Drought Severity Index (PHDI)** was presented earlier in the presentation of the PDSI. The distinction between PHDI and PDSI 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 and more slowly than the PDSI towards the normal state. Specifically, the PDSI considers that a drought episode is finished when moisture conditions begin an uninterrupted rise that ultimately erases the water deficit, whereas PHDI considers a drought ended when the moisture deficit actually vanishes. This retardation is appropriate for the assessment of hydrological drought, which is a slower developing phenomenon than meteorological drought. It should be mentioned that PDSI can be computed only when the drought event finished, i.e. only on past series, while PHDI can be computed in the current time interval.

The **Surface Water Supply Index (SWSI)**, developed by Shafer and Dezman (1982), explicitly accounts for snowpack and its delayed runoff. The mathematical formulation of the SWSI is as follows:

$$SWSI = \frac{aP_{snow} + bP_{prec} + cP_{stream} + dP_{res} - 50}{12} \quad (23)$$

where, a, b, c, d are weights for each hydrological component and $a+b+c+d = 1$, P_i is the probability of non-exceedence (in %) for component i, and snow, prec, stream, res are the snowpack, precipitation, streamflow, and reservoir storage components, respectively. Subtracting 50 and dividing by 12 are a centring and compressing procedure designed to make the value have a similar magnitude to the PDSI and make comparisons between watersheds (Garen, 1992). The weights are estimated from a basin calibrated SWSI algorithm that considers the typical contribution of each hydrological component to the water supply of the basin. The SWSI is a suitable measure of hydrological drought for mountainous regions, where snow contributes significantly to the annual streamflow.

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. The CMI can assess present conditions for crops but it can rapidly vacillate and is a poor tool for monitoring long-term drought. The CMI begins and ends each growing season near zero, which may be appropriate for botanical annuals, but not for tracking long-term droughts. As a consequence, the assessment of agricultural drought is better suited to the related Palmer Moisture Anomaly Index or Palmer Z-Index (Karl, 1986).

The **Palmer Moisture Anomaly Index (Z-Index)** has been presented earlier in the computation of 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 and it is only slightly less complex than the PDSI.

The **Soil Moisture Anomaly Index (SMAI)** was developed by Bergman and his associates (1988) to characterize droughts on a global basis. The method inherently relies upon the moisture accounting method of Thorthwaite 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. Simulation results suggest that SMAI values change at a rate centred between the rapid CMI and the relatively slow PDSI (Bergman *et al.*, 1988).

Spatial Extent of Drought

The Run Method

Use of run analysis has been proposed as an objective method for identifying drought periods and for evaluating the statistical properties of drought. According to this method a drought period coincides with a "negative run", defined as a consecutive number of intervals where a selected hydrological variable remains below a chosen truncation level or threshold (Yevjevich, 1967).

Such a threshold can be a fixed value in the case of a non-periodic (e.g. annual) stationary time series or a seasonally varying truncation level in the case of a stationary periodic series. The truncation level in each time interval is somewhat arbitrary and it must be selected on the basis of the objective of the study. Usually it is assumed equal to the long-period mean (or median) of the variable of interest, while other possible choices include a fraction of the mean (Clausen and Pearson, 1995), a value corresponding to a given non-exceedence probability (Zelenhasic and Salvai, 1987, and Correia *et al.*, 1987), or a level defined as one standard deviation below the mean (Ben-Zvi, 1987). In any case, the threshold should be chosen in such a way to be considered representative of the water demand level (Yevjevich *et al.*, 1983, Rossi *et al.*, 1992).

The advantage of using the run method for drought definition consists in the possibility of deriving the probabilistic features of drought characteristics (such as duration, cumulative deficit) analytically or by data generation, once the stochastic properties of the basic variable are known. This possibility is not limited to relatively simple cases where time dependence of consecutive values can be neglected but also when a Markov chain structure is assumed for the underlying variable (Cancelliere *et al.*, 1998; Fernandez and Salas, 1999). Furthermore, procedures to assess the return period of droughts defined according to the run method have been derived recently (Fernandez and Salas, 1999; Shiau and Shen, 2001; Bonaccorso *et al.*, 2003; Cancelliere and Salas, 2004), thus making the method an ideal candidate to perform drought risk analysis.

Drought identification and characterization both at a site and over a region based on the run method can be carried out by REDIM software, developed by the Department of Civil and Environmental Engineering of Catania University and available at the website:

http://www.risorseidriche.dica.unict.it/main_downloads.html

The Cumulative "or more" curves

A better representation of the spatial extent of the drought can be achieved using a type of curves known as cumulative "or more" curves (ogives). These curves can be produced by plotting the severity of drought (y-axis) versus the percentage of the affected area (x-axis). The severity of drought is presented by a drought index and the area refers to that affected by at least the corresponding severity level. This type of graphs can be used not only for the characterization of drought and the determination of its areal extent, but also for comparisons with the critical area percentage (related to severity) directly. Clearly, more than one thresholds referring to the percentage of critical area can be used defining different levels of severity. A representative "or more" curve is presented in Fig. 2 for the affected area, during a dry year, using the SPI as the index of drought severity.

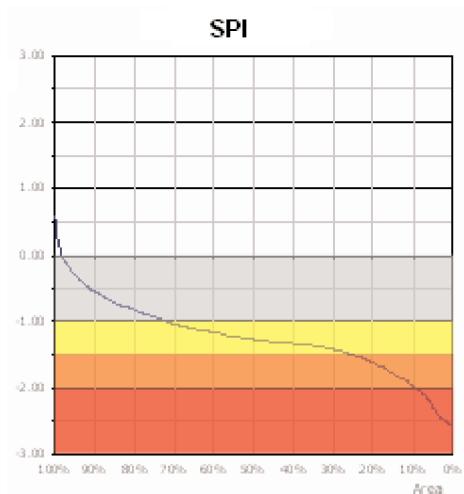


Fig. 2. The "or more" curve for a dry year using the annual SPI.

Discussion and recommendations

The basic steps for drought characterization could be summarised as follows:

- (i) Collect all the necessary monthly data of each reliable meteorological station of the selected area (or areas)
- (ii) Transfer meteorological data at a basin or sub-basin level (monthly time step should be used)
- (iii) Calculate selected indices on an appropriate time scale (e.g. annual scale)
- (iv) Display the results graphically using colours for the various levels of drought intensity
- (v) Analyze the frequency of occurrence of 1-year drought (the same can be done for a 2-year and 3-year droughts) using historical data. Use one or two of the most popular uni-variate probability distribution functions (e.g. EV I/Gumbel, Lognormal, Pearson III, etc.)
- (vi) The shortcoming of the above methodology is the fact that a limited number of droughts may be found even on rather long historical series. A method overcoming this drawback is the methodology proposed by Bonaccorso *et al.* (2003) and Cancelliere and Salas (2004).

Time scale of calculation

A common feature of all indices is that they are calculated over a particular period of time. The period of time to be considered depends on the characteristics of the systems to be analysed. For example, dryland agriculture is affected by the atmospheric phenomena (rainfall, temperature) of short periods of time (i.e., one or two months) while the rate at which shallow wells, small ponds, and smaller rivers become drier or wetter is affected by the atmospheric phenomena of longer periods (i.e., several months). Some processes have much longer time scales, such as the rate at which major reservoirs, or aquifers, or large natural bodies of water rise and fall, and the time scale of these variations is on the order of several years. Finally the time scale analysis should coincide with the critical period of the elements at risk due to drought hazard.

Basic indices to compare drought episodes

In the process of drought identification, it was concluded that the first step is to analyze meteorological and hydrological droughts using up to 4 indices for each climatic data set:

- (i) Standard Precipitation Index (SPI)
- (ii) Reconnaissance Drought Index (RDI)
- (iii) Deciles
- (iv) Surface Water Supply Index (SWSI)

The four selected indices for the risk analysis provide a relatively simple way to calculate the severity of droughts and make results comparable across sites.

The Standard Precipitation Index (SPI) developed by McKee *et al.* (1993) has been widely used by planners and in research. It can be used on a variety of time-scales and only requires precipitation data.

The Reconnaissance Drought Index (RDI) is as simple as the SPI and it incorporates the evapotranspiration. From a variety of applications, it was shown that the RDI behaves in a similar manner as the SPI. However, the results are differing when comparing droughts in different climatic regions.

The Deciles (Gibbs and Maher, 1967) method is applied by the Australian Drought Watch System to characterize and monitor drought. Its advantage relies in the simple calculation grouping precipitation into deciles, avoiding the problem of fitting a function to the data distribution which might be the case with SPI.

The Surface Water Supply Index (SWSI) (Shafer and Dezman, 1982) represents surface water supply conditions and includes water management in drought characterization. It combines hydrological and climatic features.

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