Droughts: concepts, indices and prediction

Pereira L.S., Paulo A.A.

in

Hamdy A. (ed.), Trisorio-Liuzzi G. (ed.).
Water management for drought mitigation in the Mediterranean

Bari : CIHEAM
Options Méditerranéennes : Série B. Etudes et Recherches; n. 47

2004
pages 113-144

Droughts: Concepts, Indices and Prediction

Luis S. Pereira[1] and Ana A. Paulo

1. Introduction

The sustainable use of water is a priority question for water scarce regions and for agriculture in particular. Imbalances between availability and demand, degradation of surface and groundwater quality, inter-sectorial competition, inter-regional and international conflicts, all bring water issues to the foreground. In fact, developments in controlling and diverting surface waters, exploring groundwater, and in using the resources for a variety of purposes have been undertaken without sufficient care being given to conserving the natural resource, avoiding wastes and misuse, and preserving the quality of the resource. Thus, nowadays, water is becoming scarce not only in arid and drought prone areas, but also in regions where rainfall is relatively abundant. Scarcity is now viewed under the perspective of the quantities available for economic and social uses, as well as in relation to water requirements for natural and man-made ecosystems. The concept of scarcity also embraces the quality of water because degraded water resources are unavailable or at best only marginally available for use in human and natural systems (Pereira *et al.*, 2002).

In most regions of the world, the annual withdrawal or use of water is a relatively small part (less than 20%) of the total annual internally renewable water resources. However, in water scarce regions, as is the case for the Middle East and North Africa regions, that share averages 73% of the total water resources (The World Bank, 1992). In these regions 53% of the per capita annual withdrawals for all uses including irrigation are below 1000 m^3/ca and 18% between 1000 and 2000 m3/ca. In Sub-Saharan countries, 24% of the population lives in areas where annual withdrawals are below 2000 m^3/ca and 8% below 1000 m^3/ca. More recent appraisals confirm the relevancy of the problem (e.g. Shiklomanov, 2000), which is evidenced when considering that estimates for the average annual growth of the population are the World's highest in the same regions. In addition, drought currently affects these regions, often with serious and devastating consequences.

[1] Agricultural Engineering Research Center, Institute of Agronomy, Technical University of Lisbon, Tapada da Ajuda, Lisbon, Portugal (lspereira@isa.utl.pt).

Worldwide, mainly in water scarce regions, agriculture is the sector which has the highest demand for water. Agriculture withdraws more than 85% of water in the average African, Asian and Pacific countries (Chaturvedi, 2000). As a result of its large water use irrigated agriculture is often considered the main cause for water scarcity. However, irrigated agriculture provides the livelihood of an enormous part of the world rural population and supplies a large portion of the world's food. This is particularly true in the Arab nations. At present, irrigated agriculture is largely affected by the scarcity of water resources. Efforts from international and national agencies, managers and researchers are continuously providing means and tools to innovate and develop management practices for improving water management, controlling the negative impacts of irrigation, diversifying water uses in irrigation projects, and increasing yields, water productivity and farmers incomes (Kijne *et al*., 2003; FAO, 2003). Similarly, great progress in engineering and management are producing new considerations for water use and water quality control for non-agricultural purposes, particularly for domestic consumption and sanitation.

The sustainable use of water implies resource conservation, environmental friendliness, technological appropriateness, economic viability, and social acceptability of development issues. The adoption of these sustainability facets is a priority for using water in every human, economic and social activity –human and domestic consumption, agriculture, industry, energy production, recreational and leisure uses – particularly in water scarce regions as analysed by Pereira *et al*. (2002). However, the causes for water scarcity have to be well understood and identified in order to adopt the measures and practices that are appropriate for each case. Moreover, global change may highly impact water resources availability by increasing the variability of rainfall in arid regions, the climate extremes and, particularly, the frequency and severity of droughts (Kabat *et al*., 2002). Therefore, the understanding of drought phenomena, their identification and prediction constitute a current challenge to mitigate the drought impacts in many areas around the world.

2. Water Scarcity and Drought Concepts

Water scarcity may result from a range of phenomena. These may be produced by natural causes, may be induced by human activities, or may result from the interaction of both, as indicated in Table 1.

Table 1. Nature and causes of water scarcity in dry environments

Water Scarcity Regime	Nature produced	Man induced
Permanent	Aridity	Desertification
Temporary	Drought	Water shortage

In a recent study for UNESCO these water scarcity regimes were defined and analysed in view of developing the appropriate means to cope with water scarcity (Pereira *et al*., 2002). These definitions, originally proposed by Yevjevich *et al*. (1983) are reproduced and commented below.

***Aridity** is a natural permanent imbalance in the water availability consisting in low average annual precipitation, with high spatial and temporal variability, resulting in overall low moisture and low carrying capacity of the ecosystems.*

Aridity may be defined through climatological indices such as the Thornthwaite moisture index, the Budyko radiation index of dryness, or the Unesco precipitation/evapotranspiration index (Sanderson, 1992). Under aridity, extreme variations of temperatures occur, and the hydrologic regimes are characterized by large variations in discharges, flash floods and large periods with very low or zero flows.

***Drought** is a natural but temporary imbalance of water availability, consisting of a persistent lower-than-average precipitation, of uncertain frequency, duration and severity, of unpredictable or difficult to predict occurrence, resulting in diminished water resources availability, and reduced carrying capacity of the ecosystems.*

Many other definitions of drought exist (Yevjevich, 1967, Wilhite and Glantz, 1987; Tate and Gustard, 2000). The U. S. Weather Bureau defined drought (Dracup *et al*., 1980) as a lack of rainfall so great and so long continued as to affect injuriously the plant and animal life of a place and to deplete water supplies both for domestic purposes and the operation of power plants, especially in those regions where rainfall is normally sufficient for such purposes. Generally, these definitions clearly state that drought is mainly due to the break down of the rainfall regime, which causes a series of consequences, including agricultural and hydrological hazards which result from the severity and duration of the lack of rainfall.

It is important to recognize the less predictable characteristics of droughts, with respect to their initiation and termination, as well as their severity. These characteristics make drought both a hazard and a disaster. Drought is a hazard because it is a natural accident of unpredictable occurrence but of recognizable recurrence. Drought can be a disaster because it corresponds to the failure of the precipitation regime, causing the disruption of the water supply to the natural and agricultural ecosystems as well as to other human activities.

Desertification *is a man-induced permanent imbalance in the availability of water, which is combined with damaged soil, inappropriate land use, mining of groundwater, and can result in increased flash flooding, loss of riparian* ecosystems and a deterioration of the carrying capacity of the ecosystems.

Soil erosion and salinity are commonly associated with desertification. Climate change also contributes to desertification, which occurs in arid, semi-arid and sub-humid climates. Drought strongly aggravates the process of desertification by increasing the pressure on the diminished surface and groundwater resources. Different definitions are used for desertification, generally focusing on land degradation, as it is the case of the definition proposed by the United Nations Convention to Combat Desertification: land degradation in arid, semi-arid and dry sub-humid zones resulting from various factors including climatic variations and human activities. In this definition land is understood as territory and is not restricted to agricultural land since desertification causes and impacts do not relate only with the agricultural activities but are much wider, affecting many human activities, nature and the overall living conditions of populations (Pereira *et al*., 2004). However, these definitions need to be broadened in scope to focus attention on the water scarcity issues. When dealing with water scarcity situations, it seems more appropriate to define desertification in relation to the water imbalance produced by the misuse of water and soil resources, so calling attention to the fact that the misuse of water is clearly a cause of desertification.

Water shortage *is also a man-induced but temporary water imbalance including groundwater and surface waters over-exploitation, degraded water quality and is often associated with disturbed land use and altered carrying capacity of the ecosystems.* For example withdrawals may exceed groundwater recharge, surface reservoirs may be of inadequate capacity and land use may have changed, revising the local ecosystem and altering the infiltration and runoff characteristics. Degraded water quality is often associated with water shortages and exacerbates the effects of water scarcity. There is no widely accepted definition for this water scarce regime and the term "water shortage" is often used synonymously with water scarcity. However it is important to recognize that water scarcity can result from human activity, either by over-use of the natural supply – inappropriately called man induced droughts - or by degradation of the water quality. This man-induced water scarcity is common in semi-arid and sub-humid regions where population and economic forces may make large demands on the local water resource, and where insufficient care is taken to protect the quality of the precious resource.

In terms of water management, regions having dry climates due to natural aridity are often not distinguished from drought prone areas. This rough approximation of concepts can be misleading in water management. In arid regions rainfall is low all the year around and is particularly lacking during the dry season, which may last for several months. Peoples and nations in arid areas developed appropriate skills to use and manage water in a sustainable way. These included measures to avoid waste of water, the adoption of technologies appropriate to the prevailing conditions, making successful use of water for agriculture and other productive activities, and the development of institutional and regulatory conditions that largely influenced the behaviour of rural and urban societies. These adaptations to live with limited water availability also included measures and practices to cope with extreme scarcity conditions when drought aggravated the limited water supplies.

Water scarcity due to drought needs appropriate approaches. To successfully cope with drought there is a need to understand the characteristics and consequences of those phenomena which make water scarcity due to drought very different from that caused by aridity. Dealing with water scarcity situations resulting from aridity usually requires the establishment of engineering and management measures that produce the conservation and perhaps the seasonal augmentation of the available resource. On the other hand droughts require the development and implementation of preparedness and emergency measures.

Differences in the perception of drought lead to the adoption of different definitions, which do not have general acceptance, nor have worldwide applicability, as reviewed by Wilhite and Klantz (1987) and Tate and Gustard, (2000). The controversy over perceptions of drought, and the consequent defining of them and their characteristics, does not help decision and policy makers to plan for droughts. Lack of clearly agreed definitions makes it difficult to implement preparedness measures, to apply timely mitigation measures when a drought occurs, or to adequately evaluate drought impacts.

Several authors point out that scientists, engineers, professionals, decision-makers often do not agree on whether to regard drought as a hazard or as a disaster. This difference in perception is one of the central problems of water management for drought (Grigg and Vlachos, 1990). As discussed above, drought is a hazard and a disaster. It is a hazard because it is a natural incident of unpredictable occurrence, and it is a disaster, because it corresponds to the failure of the precipitation regime, causing disruption of water supply to the natural and agricultural ecosystems as well as to human and social activities.

The perception of the hazardous nature of dependence on precipitation and water availability depends on the climatic, meteorological and hydrological regimes of the affected region, as well as on the severity of the effects. In humid climates a short period without rainfall may be considered a drought, while in an arid or semiarid environment a dry period with the same duration could be considered normal.

Some authors prefer to adopt an operational definition that distinguishes between meteorological, agricultural, and hydrological droughts. These usually focus on the indicator variable of prime interest, which could be the precipitation (meteorological drought), soil moisture (agriculture drought), stream flow discharges or groundwater levels (hydrological drought and groundwater drought). Alternative definitions result from the complexity of the hydrological process that controls the temporal and spatial distribution of rainfall via the various paths within the large-scale hydrological cycle and the global circulation of the atmosphere. In certain regions, where water supplies mainly depend upon river diversions, when dealing with a regional drought it may be necessary to consider not only precipitation but also stream-flow. However, stream flow is also a dependent variable, controlled by the current and antecedent precipitation. In many cases, where the river discharges are regulated by dams and other hydraulic structures, the drought definition may need to be more a reflection of the river management decisions than of the natural supply. Thus, the use of precipitation or stream-flow data may not be sufficient to characterize droughts at the local scale, but the definition may need to reflect the supply conditions at the river basin scale.

3. The Case Study Region of Alentejo, Portugal

The region of Alentejo, in the southern part of Portugal (latitude: 37º20′ to 39º40′ N; longitude: 6º55′ to 8º50′ W), has an area of 27×10^3 km^2 (Fig. 1) and is characterized by extensive agriculture, mainly cereals (wheat), olive trees, vineyards, Mediterranean forests (cork oak and green oak), and natural pastures. Rainfall is relatively abundant during the autumn-winter period but extremely scarce during summer (Fig. 2). Summer crops can only be grown when irrigated, while the production of non-irrigated winter and spring crops is strongly dependent upon the amount and distribution of rainfall. The region is often stricken by droughts and consequent water scarcity.

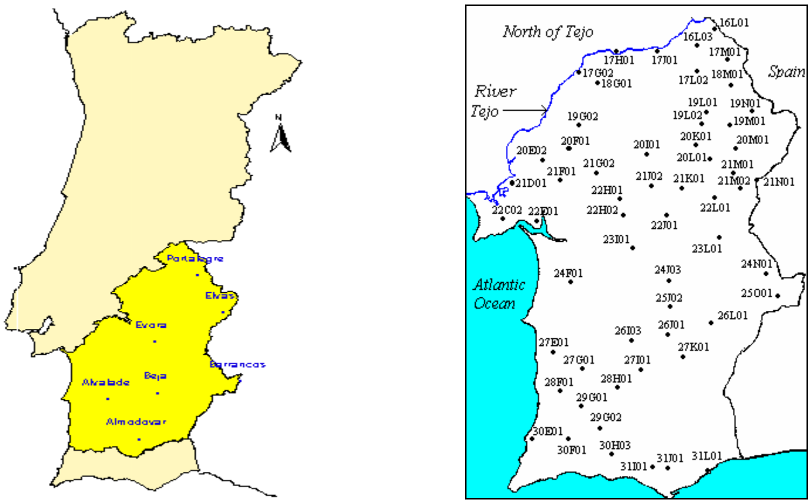

Fig. 1. Location of the Alentejo region and identification of rainfall stations utilized in the study

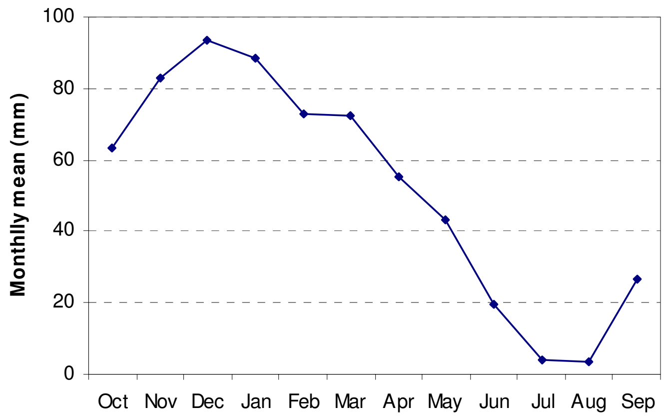

Fig. 2. Monthly mean areal precipitation in Alentejo from 49 rainfall stations for 1931/32 to 1998/99

The quality of rainfall data of 76 rainfall stations over the period 1931/32-1998/1999 was checked (Paulo *et al.*, 2003a). Annual data sets were investigated for randomness, homogeneity and absence of trends. The autocorrelation test (Kendall τ), the Mann-Kendall trend test and the homogeneity tests of Mann-Whitney for the mean and the variance were performed (Helsel and Hirsch, 1992) using software developed by Matias (1998) as reported by Paulo *et al*. (2003a). Linear models using maintenance of variance extension techniques were applied to estimate missing monthly data. These models preserve well the variance and extreme order statistics of the reference site in the filled series (Hirsch, 1982; Vogel and Stedinger, 1985). The reference site was selected according to the linear correlation coefficient between the station of interest and the other rainfall stations in the region.

Random and complete data sets from 49 rainfall stations were then used to compute monthly areal precipitation, weighting at-site precipitation by the respective areas of influence obtained by Thiessen polygons. The location of the studied rainfall stations is shown in Fig. 1.

4. Drought Identification and Characterisation at Local Level

4.1. Drought indices

The characterization of a drought using indices is also controversial and often contradictory. It is common that agronomists use the word drought to define a water stress condition affecting crop growth and yield (Maracchi, 2000). Drought could then be characterized by a crop-water stress index (e.g. Vermes, 1998). Short duration dry periods for agricultural are not considered to be droughts, but are defined as dry spells. These are characteristic of sub-humid temperate and tropical climates, and may cause relatively long periods of low soil moisture that limit agricultural activities. However they have less impact on natural ecosystems and on other human activities.

The interdependence between climatic, hydrologic, geologic, geomorphic, ecological and societal variables makes it very difficult to adopt a definition that fully describes the drought phenomena and the respective impacts. Meteorologists and hydrologists have developed indices, which depend on hydro-meteorological parameters or rely on probability. Several drought studies (e.g. Yevjevich *et al*., 1983, Wilhite *et al*., 1987; Hayes, 2003; Vogt and Somma, 2000) give examples and analyze several of these indices. Stochastic analysis including the theory of runs has been successfully applied for characterization of local and regional droughts in Mediterranean areas (Rossi *et al*., 1992; Al-Salihi, 2003; Bergaoui, 2003; Cancelliere and Rossi, 2003), particularly in Portugal (Santos, 1983; Santos *et al*., 1988; Henriques and Santos, 1996). The Standardized Precipitation Index (SPI) is receiving particular attention since it was first developed (McKee *et al*., 1993), but only more recently it has been applied to the analysis of regional droughts (Paulo and Pereira, 2002; Paulo *et al*., 2003a).

Guttman (1998) recently compared the Palmer Drought Stress Index (PDSI) with the SPI. The theory of runs and the SPI were compared for Alentejo, Portugal (Paulo *et al*., 2003a) and the SPI was also successfully compared with the PDSI for the same region (Paulo *et al*., 2003b). The SPI was applied for predicting drought class transitions using the Markov chains and Loglinear models, which has proved its usefulness for drought characterization at both local and regional scales (Paulo *et al*., 2003b)

Three main indices are analyzed in this paper for local droughts: the index of anomalies by the theory of runs, the PDSI and the SPI, which are described below.

4.2. Theory of runs

A run is a succession of the same kind of observations preceded and succeeded by one or more observations of different kind. The Theory Of Runs (TOR) is based on the choice of a critical threshold level, y_c (Guerrero-Salazar and Yevjevich, 1975). Considering a discrete time series, x_1, x_2, ..., x_i,..., x_n, a negative run occurs when xi is consecutively less than y_c, during one or more time intervals. Negative runs in rainfall time series are related to drought and the difference between y_c and x_t is referred as a deficit. A run can be characterized by its length (L), its cumulated deficit (D), and its intensity (I), as described in Figure 3.

Therefore, any drought, s, can be characterized by its:

> *duration*, *L(s)*, the number of consecutive time intervals where rainfall remains below the critical level,
>
> *cumulated deficit*, *D(s)*, the sum of consecutive deficits, and
>
> *intensity*, *I(s)*, given by the ratio *D(s)/L(s)*.

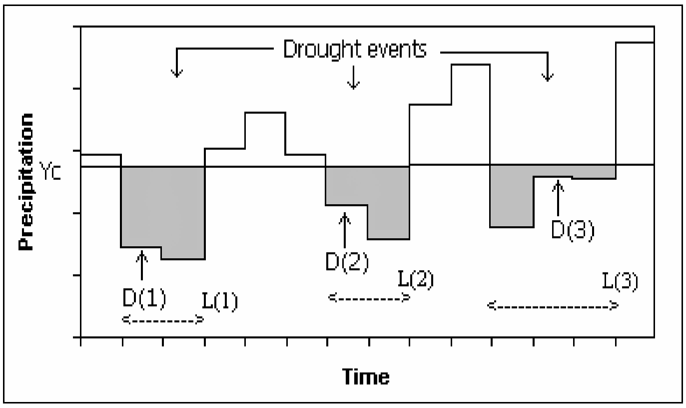

Fig. 3. Characteristics of local drought events with the theory of runs

The number of droughts and its characteristics depend upon the choice of the critical rainfall threshold level y_c. A threshold of ($\hat{\mu} - \hat{\sigma}$), i.e. a rainfall below the mean by the quantity corresponding to the standard deviation, was selected for the case study presented herein.

The analysis using the theory of runs, as well as the methods described below, require good quality of data sets. Thus, the randomness of the annual data sets should be investigated through tests for homogeneity, absence of trends and autocorrelation. A set of non-parametric tests is presented by Helsel and Hirsch (1992).

4.3. The Palmer Drought Severity Index

The Palmer Index was developed by Palmer (1965) as a meteorological index to identify and assess the severity of a drought event. The purpose of the index was to "measure the departure of the moisture supply". Since 1965 the Palmer index (PDSI) has been used as a useful tool in drought evaluation. Some limitations of the PDSI were pointed out by Alley (1984), namely the arbitrary rules to quantify the intensity, the beginning and the end of a drought event and the backtracking procedure to select the drought index. Limitations on the use of PDI to Mediterranean regions have been shown by Cancelliere *et al*. (1996). Gutmann (1998) compared the frequency of extreme drought months identified by the PDSI and by the SPI concluding that PDSI overestimates that frequency. The comparison performed for Alentejo has shown some minor limitations but demonstrated the robustness of the PDSI.

The PDSI is derived from the soil water balance, usually on a monthly basis. The input data consists on historical records of precipitation and evapotranspiration, the latter computed either by the Thornthwaite's method or from a more complete set of meteorological parameters when another method like the FAO-PM method (Allen *et al*., 1998).

The soil is conceptually divided in two layers: the surface layer, where the total available water (TAW) is 25 mm, and an underlying layer where TAW depends upon the average regional soil characteristics. It is roughly assumed that evapotranspiration removes the water from the surface layer at its potential rate, and the water extraction from the underlying layer begins after water has been removed from the surface layer. When precipitation exceeds the potential evapotranspiration the water recharge begins in the surface layer and begins the filling the subsurface layer only when that layer is replenished. Runoff takes place only when both layers reach the field capacity.

From the inputs, all the basic terms of the water balance equation can be determined, including evapotranspiration, soil recharge, runoff, and moisture loss from soil layers.

The computation of the PDSI for each time interval i is based on the moisture anomaly, z_i, obtained by multiplying the moisture departure d_i by the climatic characteristic k_j of the current month *j*, as:

$$z_i = k_j d_i \tag{1}$$

The moisture departure d_i is the deviation between the actual precipitation, P_i, and the amount of precipitation that might occur given the average conditions of the climate, $\hat{P}_i$, and is computed as:

$$d_i = P_i - \hat{P}_i = P_i - (\alpha_j ETP_i + \beta_j PR_i + \gamma_j PRO_i - \delta_j PL_i) \tag{2}$$

where ETP_i is potential evapotranspiration, PR_i is potential recharge of soil moisture, PRO_i is potential runoff and PL_i is potential soil moisture loss, all referring to the time interval i. The coefficients α_j, β_j, γ_j and δ_j are the ratios between the average of each of the actual values (ET, R, RO, and L) to the average of the corresponding potential values (ETP, PR, PRO, and PL) over a calibration period. Their subscript *j* refers to the month of the year. These coefficients are called water balance coefficients and they were conceived to adjust the potential values according to monthly changes.

There are three intermediate indices, X_1, X_2 and X_3 relative to the severity of a wet spell that may or may not be developing, the severity of a dry spell that may or may not be developing, and the severity of the current spell, respectively. These indices are computed at each interval i from the recursive equation

$$X_i = 0.897 X_{i-1} + z_i / 3 \tag{3}$$

The actual PDSI, X, is chosen from one of the three indices according to some rules, using a backtracking procedure. The classification of the PDSI values (Palmer, 1965) is displayed in Table 2.

Table 2. Classification of PDSI values and categories

PDSI values	Palmer wet and dry categories	Assigned drought categories
≥ 4.00	Extremely wet	Non-drought
3.00 to 3.99	Very wet	Non-drought
2.00 to 2.99	Moderately wet	Non-drought
1.00 to 1.99	Slightly wet	Non-drought
0.50 to 0.99	Incipient wet spell	Non-drought
0.49 to –0.49	Near Normal	Non-drought
–0.50 to –0.99	Incipient drought	Non-drought
–1.00 to –1.99	Mild Drought	Mild Drought
–2.00 to –2.99	Moderate drought	Moderate drought
–3.00 to –3.99	Severe drought	Severe drought
≤ –4.00	Extreme drought	Extreme drought

The severity of droughts by the PDSI show to be sensible to the TAW value selected for the soil and slightly sensible to the ET computation procedure (Paulo *et al.*, 2003c). Care is also required to select the values for the initial soil moisture.

4.4. Standardized Precipitation Index (SPI)

The Standardized Precipitation Index was developed by McKee *et al.* (1993) with the purpose of identifying and monitoring local droughts. Multiple time scales (McKee *et al.*, 1995), from 3-month to 24-month, may be used. Shorter or longer time scales may reflect lags in the response to precipitation anomalies. The initiation of a drought event is identified by a backtracking procedure: the drought event has its confirmation only when in a series of continuously negative values of SPI the value -1 or less is reached. A drought ends when the SPI becomes positive. Each drought event is then characterized by its:

lead-time, which is the number of months SPI ≤ –1 is reached

duration, defined by the time between its beginning and end,

severity, given by the SPI value for each month, which classification is given in Table 3.

magnitude, calculated by the sum of the SPI for every month from the initiation to the end of each drought event

intensity, ratio between the magnitude and the duration of the event.

The SPI is an index based on the probability distribution of precipitation. This index depends on the distribution function, on the sample used to estimate the parameters of the distribution, and on the method of estimation. The two-parameter gamma distribution function is often used but statistical goodness of tests are required before its adoption. The entire period of records is generally used to estimate the parameters of the gamma distribution function, e.g. by the method of maximum likelihood (Kite, 1988).

In practice the computation of the SPI index (Edwards, 2000) in a given year *i* and calendar month *j*, for a *k* time scale requires:

1. calculation of a cumulative precipitation series $X_{i,j}^{k}$ (*i=1,…,n*) for that calendar month *j*, where each term is the sum of the actual monthly precipitation with precipitation of the *k-1* past consecutive months;

2. fitting of a gamma distribution function *F(x)* to the monthly series;

3. computing the non- excedence probabilities corresponding to the cumulative precipitation values;

4. computing of SPI values by transforming those probabilities into standard normal variable values, thus the SPI values are obtained from

$$SPI_{i,j}^{k} = \frac{X_{i,j}^{k} - \hat{\mu}_{j}^{k}}{\hat{\sigma}_{j}^{k}} \qquad (4)$$

where $\hat{\mu}_{j}^{k}$ and $\hat{\sigma}_{j}^{k}$ are respectively the mean and the standard deviation of the observed totals in month *j*, with time scale *k*, for a data set of length *n*.

The SPI is a z score and represents an event departure from the mean, expressed in standard deviation units. SPI is a normalized index in time and space. This feature allows comparisons of SPI values between different locations.

Drought severity is arbitrarily defined according to the SPI values as listed in Table 3 (McKee *et al.*, 1993), where the expected time in each drought category was based on an analysis of a large number of rainfall stations across Colorado, USA. The percent of time in moderate, severe and extreme droughts correspond to those expected from a normal distribution of the SPI.

Table 3. Classification of SPI values and indicative time in category

SPI values	Drought category	Time in category
0 to −0.99	Mild drought	24.0%
−1.00 to −1.49	Moderate drought	9.2%
−1.50 to −1.99	Severe drought	4.4%
≤ −2.00	Extreme drought	2.3%
		40.0%

4.5. Application of the theory of runs, PDSI and SPI to Alentejo

In the studies performed (Paulo and Pereira, 2002; Paulo *et al.*, 2002; 2003a, b and c), the theory of runs and the SPI were applied to 12- and 3-month time scales. However, only results referring to the 12-month time scale are referred herein. The time lag of 3-month show to be short for the type of climate and vegetation in Alentejo, while the gamma distribution function did not fit well for some stations when using that time-scale.

When comparing the results for the theory of runs with those for SPI it was observed that both indices are compatible but yield a different identification of droughts (Table 4), in a larger number for the SPI. However, because the SPI is obtained from moving totals, it provides more continuous information on the variation of dryness conditions in time.

Table 4. Comparing the local droughts identified for Alentejo using the theory of runs and the 12-month SPI for the period 1931/32 to 1994/95 (Paulo *et al.*, 2003a)

	Theory of runs				SPI					
Station code	**Nr of years under drought**	**Nr of drought events**	**Mean cumul. deficit (mm)**	**Average Intensity (mm/y)**	**Nr of drought events**	**Average duration, months**	**Average time (months) in classes of severity**			
							Extreme	**Severe**	**Moderate**	**Mild**
16L03	11	10	70	62	15	21.7	1.1	2.0	5.7	12.9
17J01	10	9	94	86	15	18.7	1.6	2.3	4.3	10.5
17L02	11	10	77	68	15	18.9	0.9	3.1	4.7	10.1
17M01	13	11	66	62	14	24.3	0.4	2.6	7.0	14.3
18G01	10	9	87	76	14	20.1	0.6	3.5	5.2	10.9
18M01	7	6	106	82	17	17.1	1.2	1.6	3.8	10.6
19G02	12	10	104	88	15	17.3	1.7	3	4	8.6
19L02	10	9	76	64	17	18.5	0.7	2.8	4.7	10.3
19M01	10	7	86	67	13	23.2	0.9	3.6	5.4	13.5
20I01	11	10	70	59	15	18.3	1.1	2.9	4.3	10.1
20L01	12	9	56	38	14	23.9	0.6	2.9	6.1	14.4
21F01	12	10	86	64	17	17.7	0.6	2.8	4.8	9.5
21G02	11	9	90	66	17	15.6	1.1	2.2	4.7	7.7
21J02	7	6	114	93	15	19.7	1.7	1.4	5.3	11.2
21K01	9	6	100	57	12	24.2	1.5	3.3	5.3	14.2
21M01	8	7	95	82	13	23.5	0.4	3.3	5.4	14.5

	Theory of runs				SPI					
Station code	Nr of years under drought	Nr of drought events	Mean cumul. deficit (mm)	Average Intensity (mm/y)	Nr of drought events	Average duration, months	Average time (months) in classes of severity			
							Extreme	Severe	Moderate	Mild
21M02	11	9	85	69	13	21.1	1.5	3.3	4.7	11.6
22E01	12	11	87	74	17	17.5	1.2	2.8	3.6	9.9
22H01	9	5	148	80	14	18.9	1.0	3.6	4.9	9.4
22J01	12	9	67	54	12	24.3	0.6	4.1	6.8	13.0
24J03	11	8	113	71	13	21.6	1.7	2.2	6.2	11.5
24N01	10	7	75	64	13	23.4	0.8	3.0	5.9	13.8
25J02	9	7	98	75	17	17.5	1.1	2.0	3.5	11.0
26I03	12	8	101	79	10	24.2	3.2	3.4	6.1	11.6
26J01	10	7	96	65	13	20.2	2.2	2.3	5.1	10.7
26L01	9	7	94	77	13	22.8	1.6	2.2	5.8	13.2
27E01	13	11	84	77	13	21.5	0.8	3.6	6.6	10.6
27G01	11	9	104	86	14	19.8	1.1	3.7	4.3	10.8
27I01	10	8	107	82	17	16.7	1.2	3.0	2.4	10.1
27K01	7	7	81	81	14	22.9	1.8	2.3	3.7	15.1
28H01	11	9	100	80	15	19.7	1.1	2.9	4.4	11.4
29G01	9	7	138	120	11	24.5	2.6	3.2	4.1	14.6
29G02	9	7	123	104	15	21.8	1.1	2.9	4.8	13.1
30E01	8	7	118	93	13	22.6	1.5	2.8	4.0	14.4
30F01	11	10	164	135	16	18.1	0.7	2.9	4.7	9.8
30H03	11	9	102	78	18	16.8	0.9	1.8	4.4	9.7
31J01	9	7	145	109	16	19.3	0.8	2.0	5.2	11.4

The calibration period used to obtain the water balance coefficients for the PDSI is coincident with the period of analysis. The initial conditions of soil water content in both layers and the initial values of X_1, X_2 and X_3 influence the results over a large period. It is recommended to discard several months of initial computations because of this influence. In the present study, with a relatively short time series of weather parameters for computing ET, a rough estimate of soil water content and of drought or wet conditions in the initial month, January of 1965, was obtained from the SPI values, computed since 1932 (Paulo *et al*, 2003a).

The Palmer index was computed for selected locations referred in Fig. 1 using 3 different soil types with total available water content of 250, 200 and 150 mm. It was compared with the SPI for the same locations and time periods. An example is shown in Fig. 4. when the PDSI was computed with PET from the FAO56 (Allen *et al.*, 1998) and a soil with TAW 150 mm. Results for all locations are similar and show a generally good agreement between these two indices (Paulo *et al.*, 2003c).

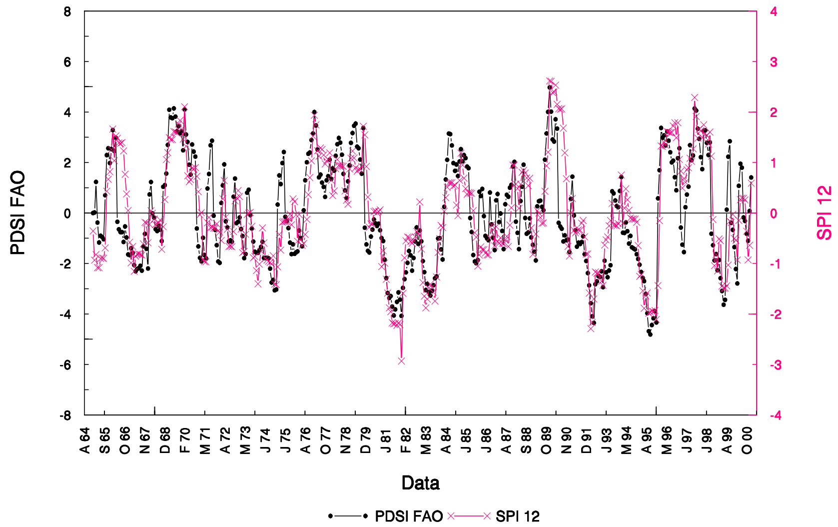

Fig. 4. Comparing the PDSI computed with the ETP-FAO56 and TAW=150 mm with the SPI computed for the time-scale 12-month at Beja, for the period 1965-2000.

Results obtained for the three indices indicate the advantage for using more than one index when operational identification of droughts is aimed. This is the option for several drought watch systems as analyzed by Rossi (2003).

5. Identification and Characterisation of Regional Droughts

5.1. Theory of runs

Regional droughts may be identified and characterized using the same methods described for identification of local droughts. A regional drought is identified when a significant fraction of the total area of the region is under drought conditions or, in other words, when the sum of the areas A_j affected by drought reaches a selected critical areal threshold A_c, as explained in Figure 5. The most common areal threshold is A_c = 50% of the total area.

Applying the theory of runs, a regional drought may be defined by its

duration, the length of the consecutive time intervals in which drought affects an area that equals or exceeds the pre-defined areal threshold;

cumulated areal deficit, the sum of the cumulated deficits at each site, weighted by the corresponding areas of influence;

regional drought intensity, the ratio between the cumulated areal deficit and the duration;

mean regional coverage, the mean fraction of the area in the region that is affected by drought.

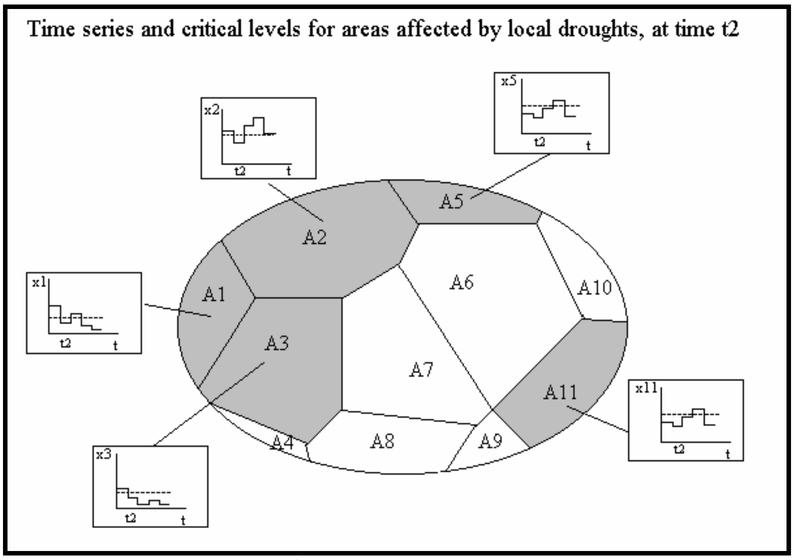

Fig. 5. Regional drought identification

5.2. Standardised Precipitation Index

The SPI may be extended to identify regional droughts and the respective regional coverage and severity. A regional drought is assumed when a significant fraction of the total area of the region is under drought conditions or, in other words, when the sum of the areas affected by local drought reaches a selected areal threshold, generally 50% of the region. At the regional scale, a month is classified to be under drought if the percent area of the region having SPI≤-1 during that month exceeds the adopted areal threshold. A regional drought event is assumed when the sum of the areas of influence of all stations affected at least by “mild drought” remains continuously above the areal threshold and, for that period, the area where SPI≤–1 exceeds the areal threshold in one or more months. For regional analysis, the SPI may be computed with several time-scales.

The following drought characteristics are computed with the SPI:

the regional drought severity, which is obtained for each month by combining the areal threshold and the local classifications of SPI for the time scale used. For example, if the total area having an SPI classification of "severe drought" equals or exceeds the areal threshold, then the region is classified under severe drought during that period;

the regional drought duration, which is the number of consecutive months when a regional drought is classified at least as “mild drought”, and that period includes one or more months where drought is classified as moderate, severe or extreme;

the monthly regional coverage under each drought category, which is the percentage of the region area affected by a drought having that severity. For example, the regional coverage of a moderate drought is the fraction of the area covered by moderate drought, which is computed from the sum of the areas of influence of all stations where $-1.5 < SPI \leq -1$;

the regional SPI (SPI_{reg}) for each month, which is the weighted average of the local SPI values using as weights the areas of influence of each rainfall station.

5.3. Application of the theory of runs and SPI to regional droughts in Alentejo

The identification and characterization of both local and regional droughts using the theory of runs was accomplished with the utilization of the software REDIM (Rossi and Cancelliere, 2003). The regional characterization of droughts with the SPI was purposefully developed for Alentejo (Paulo *et al.*, 2002; 2003a, Paulo and Pereira, 2002).

Table 5 shows the main characteristics of the droughts identified by the theory of runs for the 12-month time scale covering at least 30% of the region. Results include the initiation and end of the drought, the duration, the areal coverage (% area) and the intensity. 10 droughts are identified for the period 1932-1995 when the areal threshold is 30% of the area. This number reduces to 7 when that threshold is 50% of the area.

Table 5. Characteristics of regional droughts using the theory of runs for the 12-month time scale

Drought number	**Initiation**	**End**	**Duration (year)**	**Areal coverage (%)**	**Intensity (mm/year)**
1	1931/32	1931/32	1	30	23
2	1934/35	1934/35	1	62	39
3	1943/44	1944/45	2	81	95
4	1952/53	1952/53	1	34	26
5	1956/57	1957/58	2	43	13
6	1964/65	1964/65	1	54	27
7	1980/81	1980/81	1	100	100
8	1982/83	1982/83	1	100	95
9	1991/92	1991/92	1	86	51
10	1994/95	1994/95	1	87	76
Average drought characteristics			1.2	67.7	54.5

The characteristics of regional droughts identified by the SPI, for the 12-month time scale using the areal threshold of 50%, are presented in Table 6 including the mean areal coverage of at least moderate droughts, the number of months within different categories of drought and the SPI_{reg}. As for the local droughts, results are different. The initiation and ending of the drought periods with SPI are identified to the month while with the theory of runs only the year could be identified. Results show that the number of regional droughts identified with SPI for the same period 1932-1995 is larger then those identified with the theory of runs and so is the respective duration.

Table 6. Characteristics of regional droughts whit the SPI for 12-month time scale and Ac=50%

Drought Nr	Initiation	End	Duration (months)	Nr of months when drought is			Areal cov (%) for a moderate drought	SPI_{reg}
				Moderate	Severe	Extreme		
1	Nov-1933	Dec-1935	26	10	2	0	42.1	-0.91
2	Jan-1944	Apr-1946	28	10	7	2	64.2	-1.24
3	Jan-1949	Apr-1950	16	3	4	0	45.8	-0.87
4	Apr-1954	Jan-1955	10	2	0	0	22.6	-0.54
5	Jan-1957	Nov-1958	23	2	0	0	24.5	-0.62
6	Dec-1964	Sep-1965	10	6	0	0	51.9	-1.00
7	Jan-1971	Jan-1972	13	2	0	0	16.9	-0.49
8	Feb-1973	Sep-1976	44	6	0	0	25.0	-0.69
9	Feb-1980	Oct-1982	33	3	10	1	45.6	-0.99
10	Dec-1982	Dec-1983	13	6	5	0	72.2	-1.26
11	Apr-1991	Oct-1993	31	9	4	1	49.8	-0.94
12	Aug-1993	Sep-1995	14	5	5	0	60.2	-1.12
Average drought characteristics			21.8	5.3	3.1	0.3	43.4	-0.89
Time in category (%)			–	8	5	1	–	–

These differences are due to the concepts behind both methodologies and also relate to the approaches used. When the theory of runs is used, the areal coverage is just the average fraction of the total area in the region that is affected by drought. With the SPI, the areal coverage may be reported to different classifications of drought periods: mild, moderate or more severe drought, i.e. in the identification of regional droughts with the SPI the areal threshold is compared with the total area affected by drought, regardless its severity. Therefore, the areal coverage of moderate or more severe droughts is often lower than 30 or 50%, the areal thresholds considered. The SPI_{reg} may be used as an indicator of the severity of the drought: it ranges from –0.32 to –1.20 and from –0.49 to –1.26, with areal thresholds of 30% and 50%.

The criteria used to identify the regional droughts need further discussion. Two drought events identified with the theory of runs having an areal coverage of 100% relative to the hydrological years 1980/81 and 1982/83 (Table 5) are considered one single and long duration drought event when the SPI is used for Ac=30% but two drought events are considered when using Ac=50% (events 9 and 10 in Table 6). As shown in Figure 6, the areal coverage changes with the severity of drought considered as threshold. If it a mild drought is considered it starts by Feb-80 with a coverage of 70% of the region, reduces coverage below 50% for only one month (Nov-82) and returns immediately to 100% coverage the next month until falling below 50% by Jan-84. When a moderate drought is considered, the area coverage starts to be above 50% some months later, by Oct-80, and falls below this threshold between Nov-81 and Dec-82; then it overcomes that threshold and falls below this value by Nov-83, thus corresponding to droughts. However the SPI_{reg} is always negative indicating that a recovery may have not been produced. Therefore, regional droughts need careful analysis.

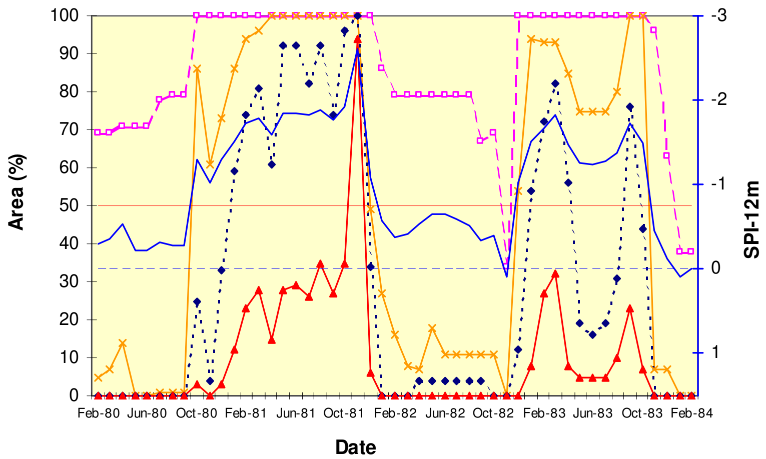

Fig. 6. Time evolution of the areal coverage relative to mild (– –□– –), moderate (—×—), severe (···◆···); and extreme (—▲—) drought categories and the SPI_{reg} (——) for the period Feb80-Feb84

The combined use of other drought indices such as the PDI are therefore required to appropriately validate a methodology relative to the use of the SPI in regional drought analysis.

6. Drought Prediction

6.1. Needs and difficulties in drought prediction

Forecasting of when a drought is likely to begin or to come to an end is extremely difficult (Cordery and McCall, 2000). However, important progress is being made in relation to the possibilities of using the El Niño Southern Oscillation (ENSO) and, to a lesser degree, the North Atlantic Oscillation (NAO) as forecasting tools (examples in Vogt and Somma, 2000). A better understanding of droughts is essential to develop tools for prediction or forecasting of drought initiation and ending, so that these occurrences may be clearly recognized. This is essential for timely and appropriate implementation of measures to cope with a drought. This is particularly important in agriculture, mainly in irrigation. Solving such difficulties requires appropriate monitoring and prediction tools, which make that drought warning becomes possible (Sivakumar and Wilhite, 2002; Rossi, 2003).

An adequate lead-time, i.e. the period between the release of the prediction and the actual onset of the predicted hazard, is more important than the accuracy of the prediction (Easterling, 1989). It is the lead-time that makes it possible for decision and policy makers to implement policies and measures to mitigate the effects of drought. In the case of agriculture, several months lead-time is essential to make it possible for farmers to take decisions to alter crop and agricultural systems to cope with drought. Difficulties in prediction have leaded some to develop early warning indices (Wilhite *et al*, 1987; Sivakumar and Wilhite, 2002). These indices can be of a meteorological or hydrological nature, combining actual and time series data, or they may result from stochastic treatment of reservoir volumes (Rossi, 2003). Researchers face, therefore, a challenge for developing prediction and early warning skills appropriate to the climatic and agricultural conditions prevailing in different drought prone areas. Autoregressive models have been applied to rainfall and drought events. The Markov chain approach applied to time series of the Palmer Index proved to be a useful tool for early warning aiming at drought management (Lohani and Loganathan, 1997; Lohani *et al.*, 1998). More recently, Ochola and Kerkides (2003) applied a Markov chain model to predict dry spells. Following previous studies on local and regional characterization of droughts in Alentejo as referred above, the behavior of SPI time series in selected sites was analyzed with Markovian and loglinear models focusing the transitions between drought categories (Paulo *et al.*, 2003b).

6.2. Using Markov chains modelling

Markov chains (Isaacson and Madsen, 1976) are used in order to estimate: (a) the probability of different drought severity classes, (b) the expected time in each class of severity, (c) the recurrence time to a particular drought class, and (d) the expected time for the SPI to change from a particular class to another. A conditional prediction scheme of drought classes was also tested. In the non-homogeneous Markov chain formulation the transition probabilities between drought states depend on the considered month; in the homogeneous formulation the transition probabilities are estimated for the whole series, with no distinction between months.

A Markov chain (Çinlar, 1975) is a stochastic process *X*, such as at any time *t*, X_{t+1} is conditionally independent from X_0, X_1, X_2, … , X_{t-1}, given X_t,; the probability that X_{t+1} takes a particular value *j* depends of the past only through its most recent value X_t:

$$P\{X_{t+1} = j | X_0, X_1, ..., X_t\} = P\{X_{t+1} = j | X_t = i\} \ \forall i, j \in S, \ t \in T \quad (5)$$

A Markov chain is characterized by a set of states, S, and by the transition probability, p_{ij}, between states. The transition probability p_{ij} is the probability that the Markov chain is at the next time point in state *j*, given that it is at the present time point in state *i*.

The form of how SPI is computed, from moving precipitation totals and the assignment of each SPI value to a drought category seem adequate to Markov chain modeling. The transition probability matrix

$$P=[p_{ij}]=P\{X_{t+1}=j|X_t=i\} \quad (6)$$

is estimated from the sample, counting the number of times that SPI passes from state *i* to state *j*, n_{ij}, by:

$$\hat{p}_{ij} = n_{ij} \Big/ \sum_j n_{ij} \quad (7)$$

The sample dimension and the number of states influence the accuracy of estimates; the number of parameters of the model depends on the number of states. In this study 4 drought categories, or states, were considered: non-drought (N), mild drought (1), moderate drought (2) and severe or extreme drought (3) with thresholds as indicated for SPI in Table 2 but grouping the severe and extremely severe classes.

The following items were estimated:

- *the drought class probabilities*, which represent the probabilities of occurrence of the various drought classes;
- *the expected residence time* in each class of severity, which is the average time the process stays in a particular drought class before migrating to another class and represents the duration of that drought class;
- *the expected first passage time* that represents the average time period taken by the process to reach for the first time the drought class j starting from some class *i*;
- *the short-term drought class prediction*, which is the most probable class one, two or three months ahead.

In the non-homogeneous formulation, 12 monthly transition probability matrices are considered because the probability of transition from state i to state j at time t depends on the month:

$$P_{ij}^{(t,t+1)} = P\left(X_{t+1} = j \middle| X_t = i\right) \quad ,\forall i, j \in S \tag{8}$$

The monthly steady-state probability vectors π (Month) are the identical rows of a stochastic matrix (Isaacson and Madsen, 1976) computed from the successive product of the monthly transition probability matrices.

In the non-homogeneous formulation, the computation of the expected time in each class of severity, the expected first passage time, and the short-term drought class prediction are dependent of the initial month since the transition probabilities between states are defined for each month.

To exemplify the analysis being performed on drought class transitions, the expected first passage time to the non-drought class is presented in Table 7. Apparently, differences between sites are not important. The average time to return to a non-drought class is related with a given drought severity recovery time and increases with the considered severity of the initial class.

Table 7. Expected time to reach the Non-drought class from any drought class (months)

	Initial drought class		
Site	**Mild**	**Moderate**	**Severe or Extreme**
Portalegre	9.72	13.63	15.53
Elvas	13.32	17.46	19.25
Evora	11.91	17.57	19.39
Beja	10.50	14.94	17.57
Barrancos	9.51	13.79	15.17
Alvalade	9.67	15.55	16.61
Almodovar	12.10	16.66	19.64
Alentejo region	12.68	16.56	19.98

Given an initial state, the more probable classes, one, two and three months ahead, are shown in Table 8 for some locations and the region, which is characterized with the regional SPI. As the Markov transition probability matrices show a strong diagonal tendency, these short-term forecasts reflect the persistence of recent weather categories: when the actual state is "Non-drought" or "Mild drought" the more probable state 1, 2 or 3 months ahead is the present state, i.e. no changes of state are predictable.

Table 8. More probable state one, two and three months ahead given an initial state

Portalegre	**1 month ahead**		**2 months ahead**		**3 months ahead**	
Initial State	**State**	**Probability**	**State**	**Probability**	**State**	**Probability**
N	**N**	**0.892**	**N**	**0.809**	**N**	**0.746**
1	1	0.775	1	0.637	1	0.548
2	2	0.520	1	0.396	1	0.429
3	3	0.646	3	0.465	3	0.359
Elvas	**1 month ahead**		**2 months ahead**		**3 months ahead**	
Initial State	**State**	**Probability**	**State**	**Probability**	**State**	**Probability**
N	**N**	**0.915**	**N**	**0.846**	**N**	**0.789**
1	1	0.803	1	0.678	1	0.595
2	2	0.587	2	0.423	1	0.462
3	3	0.516	2	0.501	2	0.453
Alentejo region	**1 month ahead**		**2 months ahead**		**3 months ahead**	
Initial State	**State**	**Probability**	**State**	**Probability**	**State**	**Probability**
N	**N**	**0.915**	**N**	**0.846**	**N**	**0.790**
1	1	0.818	1	0.696	1	0.611
2	2	0.605	1	0.407	1	0.412
3	3	0.762	3	0.603	3	0.492

N Non-drought; 1 Mild drought; 2 Moderate drought; 3 Severe or Extreme drought

Despite limitations in the stochastic modeling applied, the differences in behavior relative to the 3 data sets presented and referring to the moderate and more severe droughts open a window on the prediction capabilities.

In the non-homogeneous formulation, the computation of the expected time in each class of severity, the expected first passage time, and the short-term drought class prediction are dependent of the initial month since the transition probabilities between states are defined for each month. The expected first passage times to a "Non-drought" state for October, January and April are presented in the Table 9.

Table 9. Expected time (months) to reach the non-drought class N from any drought class given the initial month

Initial class	Portalegre	Elvas	Évora	Beja	Barrancos	Alvalade	Almodovar	Alentejo region
	Initial month: October							
Mild	7.9	10.5	10.0	9.5	9.4	7.7	10.2	10.1
Moderate	10.6	16.9	15.7	13.5	12.8	13.5	16.1	14.6
Severe/Extreme	11.9	17.7	19.0	14.5	13.3	13.9	16.4	14.2
	Initial month: January							
Mild	8.6	13.9	11.4	9.8	9.0	8.6	11.6	12.9
Moderate	15.0	18.3	17.9	16.5	14.9	15.7	18.4	17.8
Severe/Extreme	17.9	21.5	20.3	19.9	16.5	19.1	21.6	19.8
	Initial month: April							
Mild	11.5	15.2	12.2	11.3	8.7	12.0	12.5	13.8
Moderate	14.2	18.5	18.7	14.7	15.6	14.1	19.0	17.9
Severe/Extreme	16.0	19.8	19.4	18.6	14.8	18.1	21.0	18.2

Results show that the time to reach a non-drought condition from an extreme or severe drought month is higher in January followed by April and October, in all studied locations. These results may be interpreted as indicating that when a severe drought is installed during the winter rainy months (Fig. 2) such as January more time is necessary for the recovery of the normal situation because rainfall is lacking during that rainy season. When drought is installed in April, since the following months are not rainy, also a long period is required. As expected, the higher is the severity of drought more time is necessary to return to a non-drought condition.

6.3. Using Loglinear models

Several loglinear models (Nelder, 1974; Agresti, 1990) are fitted to the drought class transition matrices. The choice of the model that shows the best fit and the subsequent estimate of the logarithm of some odds of interest and of the respective confidence intervals are presented. Results prove the utility of these models to a better understanding of the evolution of drought processes and to produce early warning of droughts and drought evolution.

The use of loglinear models (Agresti, 1990) aims at modeling the expected frequencies of class transitions, hereon denoted by E_{ij}. The corresponding observed frequencies refer to the drought class transitions based on the SPI index computed on a twelve-month time scale. These observed frequencies are the response variable for the loglinear models. Several models were fitted to the response variable. The residual deviance combined with the degrees of freedom (d.f.) of the residuals allows to assess the goodness of fit of the models. The p-value indicates the probability that the sample has been drawn from a population corresponding to the model assumed in the null hypothesis. The quasi-association and the quasi-symmetry models (Agresti, 1990) prove to be the more adequate to model drought class transitions.

The observed and expected (modeled) frequencies E_{ij} of drought class transitions computed with the fitted Loglinear models are presented in Table 10. Results evidence an excellent agreement between observed and expected values.

Table 10. Drought class transitions between time t and t+1: observed versus expected frequencies

	State (droughtclass) at time *t*	Observed				Expected			
		State at time *t*+1				State at time *t*+1			
		N	1	2	3	N	1	2	3
Portalegre	N	346	39	3	0	346	39.99	1.92	0.08
	1	41	227	21	4	40.06	227	21.99	3.95
	2	1	22	39	13	1.86	21.17	39	12.97
	3	0	4	13	31	0.08	3.83	13.08	31
Elvas	N	344	31	0	1	344	31.49	0	0.51
	1	32	245	25	3	31.51	245	26.46	2.03
	2	0	27	54	11	0	25.54	54	12.46
	3	0	1	14	16	0.49	1.97	12.54	16
Alentejo	N	356	32	1	0	356	31.48	1.48	0.03
	1	31	243	21	2	31.54	243	20.38	2.08
	2	2	19	46	9	1.43	19.68	46	8.89
	3	0	2	8	32	0.03	1.84	8.13	32

N-Non-drought 1-Mild drought 2-Moderate drought 3-Severe or Extremely severe drought

Results in Table 10 show a diagonal tendency indicating that, given an initial state at time t, the more probable classes, one, two and three months ahead are those initial, i.e., in agreement with results relative to Markov chain modeling (Table 7). These short-term forecasts reflect the persistence of recent weather categories. Results also show that passing from a given drought class to a less severe one is more probable that to pass to a more severe class.

With Loglinear models it is possible to compute how most probable is the transition from class *i* to class *j* compared with the transition from class *k* to class *l* when analyzing the value of the odds, defined by the ratio E_{ij}/E_{kl}, where E_{ij} and E_{kl} are the expected frequencies of transitions from class *i* to class *j* and from class *k* to class *l*. Results already available relative to the analysis of odds are promising. Nevertheless, more research is required, including for the application of the stochastic models to other indices and not only the SPI.

7. Conclusions

The analysis presented above shows that drought indices greatly help to identify and characterize local and regional droughts. The indices relative to the theory of runs and the SPI are more easy to use because they require rainfall data only while the PDSI needs weather data to estimate the evapotranspiration. It is therefore difficult to use at regional scale. The combined use of different indices that may have differences in behavior but that show to yield coherent results is quite important to effectively identify the onset of droughts, their evolution and end.

The prediction capability of the Markov homogeneous and non-homogeneous modeling concerning short-term forecasts is limited by the characteristics of the climate, which tends to be reproduced in the short-term forecasts. However, the probabilities of transition from a given drought class in a given month to all possible drought classes in the near future months can be mapped. Results from Markov chains modeling may be combined with those of Loglinear models and the respective probabilities may be better interpreted in an operational perspective. Moreover, the analysis of these probabilities combined with other indicators such as actual and historical soil moisture conditions, reservoir levels and streamflow records may contribute to support decisions in the context of water management, including relative to early warning. This prediction analysis should be part of the preparatory measures to combat droughts, and is essential for the timely implementation of mitigation measures (Pereira *et al.*, 2002).

Acknowledgements

Data used in this study were made available by the Institute for Water (INAG), Portugal. This study was funded through the national project PEDIZA 1999.64.006326.1, and is now part of the research contract INTERREG III B MEDOC 2002-02-4.4-1-084.

References

Agresti A., 1990. Categorical Data Analysis. J. Wiley&Sons, New York.

Al-Salihi A., 2003. Drought identification and characterization in Jordan. In: Rossi G., Cancelliere A., Pereira L.S., Oweis T., Shatanawi M., Zairi A. (Eds.) Tools for Drought Mitigation in Mediterranean Regions, Kluwer, Dordrecht, pp. 89-102.

Allen R.G., Pereira L.S., Raes D., Smith M., 1998. Crop Evapotranspiration. Guidelines for Computing Crop Water Requirements. FAO Irrig. Drain. Pap. 56, FAO, Rome, 300p.

Alley W.M. 1984. The Palmer Drought Severity Index: limitations and assumptions. J.Climate and Applied Meteorology, 23:1100-1109.

Bergaoui M., 2003. Local and regional droughts in Siliana' catchment, Tunisia. In: Rossi G., Cancelliere A., Pereira L.S., Oweis T., Shatanawi M., Zairi A. (Eds.) Tools for Drought Mitigation in Mediterranean Regions, Kluwer, Dordrecht, pp. 79-88.

Cancelliere A., Rossi G., 2003. Droughts in Sicily and comparison of identified droughts in Mediterranean Regions. In: G. Rossi, A. Cancelliere, L.S. Pereira, T. Oweis, M. Shatanawi, A. Zairi (Eds.) Tools for Drought Mitigation in Mediterranean Regions, Kluwer, Dordrecht, pp. 103-122.

Cancelliere A., Rossi G., Ancarani A., 1996. Use of Palmer index as a drought indicator in Mediterranean regions. In: Proc. IAHR Congress From Floods to Drought, Cape Town, South Africa.

Chaturvedi M.C., 2000. Water for food and rural development: developing countries. Water Internat. 25(1): 40-53.

Çinlar E., 1975. Introduction to Stochastic Processes. Prentice-Hall, New Jersey.

Cordery I., McCall M., 2000. A model for forecasting drought from teleconnections. Water Resour. Res. 36, 763-768.

Dracup J.A., Lee K.S., Paulson E.D., 1980. On the definition of droughts, Water Resour. Res. 16(2), 297-302.

Easterling W.E., 1989. Coping with drought hazard: recent progress and research priorities. In: Siccardi F, Bras R.L. (Eds.) Natural Disasters in European Mediterranean Countries. US National Science Foundation and National Research Council of Italy, Perugia, pp. 231-270.

Edwards D., 2000. SPI defined. In: http://ulysses.atmos.colostate.edu/SPI.html, Colorado.

FAO, 2003. Unlocking the Water Potential of Agriculture, FAO, Rome.

Grigg N.S., Vlachos E.C., (Eds.) 1990. Drought Water Management (Proc. Nat. Workshop, Washington DC). Colorado State University, Fort Collins.

Guerrero-Salazar P., Yevjievich V., 1975. Analysis of Drought Characteristics by the Theory of Runs. Hydrology Paper Nr. 80, Colorado State University, Fort Collins.

Guttman N.B., 1998. Comparing the Palmer drought index and the standardized precipitation index. J. Am. Water Res. Assoc., 34(1), pp. 113-121.

Hayes M., 2003. Drought indices. National Drought Mitigation Center, Lincoln, Nebraska.

Helsel D.R., Hirsch R.M., 1992. Statistical Methods in Water Resources. Elsevier, Amsterdam.

Henriques A.G., Santos M.J.J, 1996. Modelo de caracterização de secas regionais. In: II Congresso da Água, APRH, Lisboa, vol.II, pp. 49-59.

Hirsch R.M., 1982. A comparison of four streamflow record extension techniques. Water Resour. Res. 18(4), 1081-1088.

Isaacson D.L., Madsen R., 1976. Markov Chains: Theory and Applications, John Wiley, New York.

Kabat P., Schulze R.E., Hellmuth M.E., Veraart J.A. (eds), 2002. Coping with Impacts of Climate Variability and Climate Change in Water Management: A Scoping Paper. International Secretariat of the Dialogue on Water and Climate, Wageningen.

Kijne J.W., Barker R., Molden D. (eds) 2003. Water Productivity in Agriculture: Limits and Opportunities for Improvement, CAB International, London.

Kite G.W., 1988. Frequency and Risk Analysis in Hydrology. Water Resources Publications, Fort Collins, Colorado.

Lohani V.K., Loganathan G.V., 1997. An early warning system for drought management using the Palmer drought index, J. American Water Resources Association 33(6): 1375-1386.

Lohani V.K., Loganathan G.V., Mostaghimi S., 1998. Long-term analysis and short-term forecasting of dry spells by the Palmer drought severity index, Nordic Hydrology 29(1), 21-40.

Maracchi G., 2000. Agricultural drought – a practical approach to definition, assessment, and mitigation strategies. In: Vogt J.J., Somma F. (Eds.) Drought and Drought Mitigation in Europe. Kluwer, Dordrecht, pp. 63-75.

Matias P.G., 1998. Análise de Frequência de Séries Hidrológicas Anuais. DER/ISA, Lisbon.

McKee T.B, Doesken N.J., Kleist J., 1993. The relationship of drought frequency and duration to time scales. In: 8th Conference on Applied Climatology. Am. Meteor. Soc., Boston, pp. 179-184.

McKee T.B., Doesken N.J., Kleist J., 1995. Drought monitoring with multiple time scales. In: 9th Conference on Applied Climatology, Am. Meteor. Soc., Boston, pp. 233-236.

Nelder J.A., 1974. Loglinear models for contingency tables: a generalization of classical least squares. Appl. Statistics, 23, 323-329.

Ochola W.O., Kerkides P., 2003. A Markov chain simulation model for predicting critical wet and dry spells in Kenia: analysing rainfall events in the Kano plains. Irrig. and Drain. 52(4): 327-342.

Palmer W., 1965. Meteorological Drought. U.S. Weather Bureau, Res. Paper N0 45, Washington

Paulo AA, Pereira LS, 2002. Analysis of the regional droughts in Southern Portugal using the standardized precipitation index. In: Maiga AH, Pereira LS, Musy A, (Eds.) Sustainable Water Resources Management: Health and Productivity in Hot Climates (Proc. Inter-Regional Conference Envirowater 2002, Ouagadougou, Nov. 2002), EIER, Ouagadougou, pp. 83-93.

Paulo A.A., Pereira L.S., Matias P.G., 2002. Analysis of the regional droughts in southern Portugal using the theory of runs and the standardized precipitation index. In: Drought Mitigation and Prevention of Land Desertification (Proc. Intern. Conf., Bled, Slovenia), Slov. Nat. Com. on Irrig. and Drain., Ljubljana, CD-ROM paper 64.

Paulo A.A., Pereira L.S., Matias P.G., 2003a. Analysis of local and regional droughts in southern Portugal using the theory of runs and the Standardized Precipitation Index. In: G. Rossi, A. Cancelliere, L.S. Pereira, T. Oweis, M. Shatanawi, A. Zairi (Eds.) Tools for Drought Mitigation in Mediterranean Regions, Kluwer, Dordrecht, pp. 55-78.

Paulo A.A., Coelho C., Pereira L.S., 2003b. Drought class transition analysis through Markov and Loglinear models. In: J.M.Tarjuelo, F.M. de Santa Olalla, L.S.Pereira (Eds.) Envirowater 2003. Land and Water Use Planning and Management (Proceedings 6th Inter-Regional Conference on Environment-Water, Albacete, Sep. 2003), CREA – Univ. Castilla-La Mancha, Albacete, pp. 35-36, paper A-098 in CD-ROM.

Paulo A.A, Pereira LS, Ferreira E, 2003c. O índice de Palmer e o índice normalizado de precipitação na identificação de períodos secos. In. JPL Ferreira *et al*. (eds.) 6º Simpósio de Hidráulica e Recursos Hídricos dos Países de Língua Oficial Portuguesa (APRH/ABRH/AMCT/INGRH, Praia, Cabo Verde, Nov. 2003), APRH, Lisboa, pp. 293-307.

Pereira L.S., Cordery I., Iacovides I., 2002. Coping with Water Scarcity. UNESCO IHP VI, Technical Documents in Hydrology No. 58, UNESCO, Paris, 267 p. (available on line: http://unesdoc.unesco.org/images/0012/001278/127846e.pdf).

Pereira L.S., Louro V., Rosário L., Almeida A., 2004. Desertification, territory and people, a holistic approach in the Portuguese context. In: J.L. Rubio (ed.) Desertification in the Mediterranean Region: a Security Issue. NATO Sc.Com., Kluwer, Dordrecht (in press).

Rossi G., 2003. Requisites for a drought watch system. In: G. Rossi, A. Cancellieri, L.S. Pereira, T. Oweis, M. Shatanawi, and A. Zairi (Eds.) Tools for Drought Mitigation Mediterranean Regions, Kluwer, Dordrecht, pp. 147-157.

Rossi G., Cancelliere A., 2003. At-site and regional drought identification with REDIM model. In: Rossi G., Cancelliere A., Pereira L.S., Oweis T., Shatanawi M., Zairi A. (Eds.) Tools for Drought Mitigation in Mediterranean Regions,. Kluwer, Dordrecht, pp. 37-54.

Rossi G., Benedini M., Tsakiris G., Giakoumis S., 1992. On regional drought estimation and analysis. Water Resour. Manag, 6, 249-277.

Sanderson M., (Ed.), 1992. UNESCO Sourcebook in Climatology for Hydrologists and Water Resource Engineers. UNESCO, Paris.

Santos M.A., 1983. Regional droughts: a stochastic characterization. J. of Hydrology 66: 183-211.

Santos M.A., Correia F. N., Rodrigues R., 1988. Risk assessment of regional droughts. In: F. Siccardi and R. L. Bras (eds.) Natural Disasters in European Mediterranean Countries, U. S. Nat. Sci. Foundation and Nat. Res. Council, Italy, pp. 333-350.

Shiklomanov I.A., 2000. Appraisal and assessment of world water resources. Water Internat. 25: 11-32.

Sivakumar M.V.K., Wilhite D.A., 2002. Drought preparedness and drought management. In: Drought Mitigation and Prevention of Land Desertification (Proc. Intern. Conf., Bled, Slovenia), UNESCO and Slov. Nat. Com. ICID, Ljubljana, CD-ROM paper 2.

Tate E.L., Gustard A., 2000. Drought definition: a hydrological perspective. In: Vogt J.J., Somma F. (Eds.) Drought and Drought Mitigation in Europe. Kluwer, Dordrecht, pp. 23-48.

The World Bank, 1992. World Development Report 1992: Development and the Environment. Oxford University Press, New York.

Vermes L., 1998. How to Work Out a Drought Mitigation Strategy. ICID Guide, 309/1998, Bonn.

Vogel R.M., Stedinger J.R., 1985. Minimum variance streamflow record augmentation procedures. Water Resour. Res. 21(5): 715-723.

Vogt J.V., Somma F., (Eds.), 2000. Drought and Drought Mitigation in Europe. Kluwer, Dordrecht.

Wilhite D.A., Glantz M.H., 1987. Understanding the drought phenomenon: the role of definitions. In: Wilhite D.A., Easterling W.E., Wood D.A. (Eds.) Planning for Drought. Vestview Press, Boulder, CO, pp. 11-27.

Wilhite D.A., Easterling W.E., Wood D.A., (Eds.), 1987. Planning for Drought. Toward a Reduction of Societal Vulnerability. Westview Press, Boulder and London.

Yevjevich V., 1967, An Objective Approach to Definitions and Investigations of Continental Hydrologic Drought, Hydrology Paper Nr. 23, Colorado State University, Fort Collins, CO.

Yevjevich V., Cunha L.V., Vlachos E., (Eds.), 1983, Coping With Droughts, Water Resources Publications, Littleton, Colorado.