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Towards a Drought Watch System based on Spatial SPI

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Abstract. Regional Drought can be assessed through various meaningful procedures mainly related to the expected consequences. However, a general knowledge of the occurrence of drought, the area which is affected, its severity and its duration are of great importance for a series of decisions, which may be appropriate for a variety of activities. From the existing simple and popular indices used for the estimation of drought, the Standardised Precipitation Index, known as SPI, seems to win universal applicability. A method based on the estimation of SPI over a geographical area and its use for characterising drought, is presented in this paper. Applications of the method are presented using a digital terrain model and a simple computer calculating routine. It is shown that the proposed procedure can be easily applied and can support a Drought Watch System for an area of mesoscale dimensions.

Key words: drought, Drought Index, DTM, mesoscale, precipitation, spatial analysis, SPI

1. Introduction

Drought is one of the major weather related hazards. However, there is no universally accepted definition of drought. Perhaps the most general of the proposed definitions is the one formulated by Bernan and Rodier (1985), 'drought is a decrease of water availability in a particular period and over a particular area'. In other words 'Drought occurs when a significant water deficit that spreads both in time and space takes place' (Correia *et al.*, 1991).

Drought definitions are continually being updated, particularly to take account of impacts on the environment and society. It is logical to accept that, drought is highly related to the time, the duration, and the place of its occurrence. Drought definitions require further development to include the impact on the ecosystems. According to Tate *et al.* (2000) the relationship between rainfall variability and impacts can depend upon the specifics of a particular agro-ecological zone or the economy.

A general agreement exists in distinguishing among aridity and drought. Aridity refers to a more or less permanent climatic condition. Drought refers to a temporary condition characterised by a 'severe' reduction of water availability compared to the normal values extending along a significant period of time and over a large region. Of course, the interpretation to be given to each of the defining terms such as 'severe reduction', 'significant period' and 'large region' introduces a strong subjectivity in the definition of drought (Rossi *et al*., 1992).

It is widely accepted that drought conditions in an area caused by consequences of various processes in the atmosphere and by the characteristics of the area. The most important of these reasons are:

- precipitation (amount, regime, time distribution and intensity),
- evapotranspiration defined by the solar radiation, air temperature, water vapour pressure and wind velocity,
- soil and vegetation cover characteristics (e.g. water retention capacity, infiltrability of the soil, albedo).

Recent methods estimate drought according to the potential damages in the various economic sectors of the suffering area. These comprehensive approaches are based on thorough simulation techniques and use data, which cannot be found easily (Tsakiris, 1994).

For simplicity purposes most popular methods for drought assessment are based on a simplified soil water balance that is directly related to drought conditions (Thornthwaites's method) or on precipitation data directly.

Some of the most popular indices of drought of the above categories are presented below, such as the Palmer Drought Severity Index (PDSI) and the Standardised Precipitation Index (SPI).

This study finally adopts SPI since this index is more objective, it is easy to use, and can be the basis for a universal application.

2. Drought Indices

2.1. PALMER DROUGHT SEVERITY INDEX (PDSI)

The Palmer Drought Severity Index (PDSI) was developed by Palmer, in 1965, in the United States. PDSI is a soil moisture algorithm calibrated for relatively homogeneous regions and specifically semi-arid and dry subhumid climatic regions (Guttman *et al*., 1992). Extrapolation beyond the circumstances for which it was designed may lead to unrealistic results. The index is based on the supply and demand concept of the water balance equation, taking into account the current weather and soil conditions and the normal climate of the area. All the basic terms of the water balance equation can be determined from the inputs, including evapotranspiration, soil recharge, runoff and moisture loss of the surface layer. However, the human impacts on the weather balance, such as irrigation, are not considered.

The PDSI is a meteorological drought index. The concept of the method is that the amount of precipitation required for the normal opeation of a local established economy, is depended on the average climate of the area and on the prevailing meteorological conditions both during and preceding the period under consideration (Tate *et al.*, 2000). The index is calculated based on precipitation and temperature data, as well as the local Available Water Content (AWC) of the soil and is not taking into account streamflow, lake and reservoir levels and other longer-term hydrologic impacts.

2.2. PRECIPITATION ANOMALY

Indices based solely upon rainfall have a wide application in many regions around the world. They have been used with great success in regions, where rainfall is normally received at fairly frequent intervals and 'droughts' or 'dry spells' appear in short periods. In these territories crop and water-storage operations are not geared to the long spells of rainless weather, which are seasonally normal in semi-arid regions (Tate *et al.*, 2000). Indices of this type are, the 'Foley Drought Index', which compares the excess of deficiencies of monthly rainfall with the respective long-term average in order to produce a graph of cumulative departures.

One of the simplest indices of precipitation anomaly is the 'Percent of Normal Rainfall'. It is calculated by dividing actual precipitation by normal precipitation, typically considered to be a 30 yr mean, and multiplying by 100% (Hayes, 1999). This can be calculated for a variety of time scales ranging from a single month to an annual or water year. Analysis using the percentage of normal is very effective when used for a single region or a single season, but can be easily misunderstood and can give different indications of conditions, depending on the location and season.

In the applications of this paper these types of maps are produced together with maps of SPI.

2.3. STANDARDISED PRECIPITATION INDEX (SPI)

The Standardised Precipitation Index (SPI) was designed by McKee and his colleagues at Colorado State University to be a relatively simple index. A deficit of precipitation has different impacts on the groundwater, reservoir storage, soil moisture, snowpack and streamflow. The SPI was designed to quantify the precipitation deficit, based on the probability of precipitation for multiple time scales, reflecting the impact of drought on the availability of the different water resources (Hayes, 1999).

The SPI is less complex than the Palmer index and can be applied to any location, although it was developed for use in Colorado. Its calculation is based on the long-term precipitation record for a desired period. This long-term record is fitted to a probability distribution, which is then transformed to into a normal distribution so that the mean SPI for the location and desired period is zero.

2.4. OTHER METHODS

Several other methods have been used worldwide to define drought. The ‘Percentile Method’ according to which, conclusions about the severity of a given value of a meteorological element can be drawn from the percentile value determined from the cumulative frequency of the value. The ‘Deciles of Precipitation’ method which groups monthly precipitation occurrences into deciles, so ‘much lower than normal’ weather can not occur more often than 20% of the time (Hayes, 1999). The ‘Surface Water Supply Index’ designed to incorporate both hydrological and climatological features into a single index value resembling the Palmer Index for major basins. The ‘Poisson Process’ according to which, when the distribution functions of the two random variables, namely the maximum dry period within a season and the waiting time to experience the first critical dry period, are given, then the statistical moments for both cases can be computed. The ‘Palfai Drought Index’ which is the ratio of the mean temperature during the period from April to August and the rainfall from October to August (Tate *et al*., 2000).

3. The Theory

As explained the Standardised Precipitation Index is based on precipitation alone and was designed to be a relatively simple, year-round index applicable to the water supply conditions giving information in support of PDSI.

Calculation of the SPI requires a long-term monthly precipitation data base with 30 yr or more of data. The index is calculated by taking the difference of the precipitation from the mean for a particular time scale and then dividing it by the standard deviation. That is:

$$DPI = \frac{x_i - \overline{x}}{\sigma}, \tag{1}$$

where

x_i = the precipitation of the selected period during the ith year; and

$\overline{x}$ and σ = the mean and the standard deviation of the selected period.

McKee originally used an incomplete gamma distribution to calculate the SPI. Efforts to standardise the SPI computing procedure have been made since then. The probability distribution function is determined from a long-term data record by fitting a function to the data. The cumulative distribution is then transformed using equal probability to a normal distribution with a mean of zero and standard deviation of one so the values of the SPI are really in standard deviations. Positive SPI values indicate greater than median precipitation, while negative values indicate less than median precipitation. A drought event occurs any time the SPI is continuously negative and reaches an intensity where the SPI is –1.0 or less. The event ends when the SPI becomes positive. The magnitude of departure from zero represents a probability of occurrence so that decisions can be made based

Table I. SPI categories according to the initial classification

SPI values	Category
2.00 and above	Extremely wet
1.50 to 1.99	Very wet
1.00 to 1.49	Moderately wet
–0.99 to 0.99	Near normal
–1.00 to –1.49	Moderately dry
–1.50 to –1.99	Severely dry
–2.00 and less	Extremely dry

on this SPI value. Because the SPI is normalised, wetter and drier climates can be represented in the same way, and wet periods can also be monitored using the SPI. Because SPI values fit a typical normal distribution, one can expect these values to be within one standard deviation approximately 68% of the time, within two standard deviations 95% of the time, and within three standard deviations 99% of the time (Wilhite *et al*., 2000).

The SPI has the ability to quantify the precipitation deficit for multiple time scales. These time scales reflect the impact of drought on the availability of water resources. Streamflow, groundwater and reservoir storage reflect the longer-term precipitation anomalies, while soil moisture conditions respond to precipitation anomalies on a relative short scale. For these reasons, the SPI was originally calculated for 3, 6, 12, 24 and 48 month time scales. A 3-month SPI reflects short and medium term moisture conditions and provides a seasonal estimation of precipitation. It compares the precipitation over a specific 3-month period with the precipitation totals from the same 3-month period for all the years included in the historical record. A relatively normal 3-month period could in the middle of a longer-term drought that would only be visible at longer time scales. The 3-month SPI can be misleading in regions where it is normally dry during that 3-month period. A 6-month SPI can be very effective showing the precipitation over distinct seasons, indicating medium-term trends in precipitation. Information from a 6-month SPI may be associated with anomalous stream flows and reservoir levels. The SPI is considered to be more sensitive to conditions at this time than the Palmer Index. A 12-month SPI reflects long-term precipitation patterns. The longer SPI tend towards zero unless a specific trend is taking place. At these time scales, SPIs are probably tied to streamflows, reservoir levels, and even groundwater levels.

An SPI classification scale is used to identify drought conditions according to the SPI values. Even though various categorisations have been suggested, most of the scientists use the initial classification shown in Table I. According to Hayes (2000), the term ‘dry’ is used because that is more appropriate for short time scales, and the categories reflect the lower percentages that should occur with the labels 'sever' and 'extreme'.

The value assigned to the SPI for drought classes were questioned by Agnew (2000), who suggested alternative, more rational thresholds. His proposal is based on probability classes rather than magnitudes of the SPI and is therefore suggested as a more rational approach. It should be noted that SPI has not been widely applied and tested since it is a relatively new index.

The SPI has a number of advantages over the PDSI. It is a simple index based only on precipitation, while PDSI requires complex calculations. The SPI is versatile. It can be calculated on any time scale, which gives the SPI the capability to monitor conditions important for various kinds of applications. This versatility is also critical for monitoring the dynamics of a drought, including its onset and end. This has been a difficult task for other indices. Because it is based only on precipitation and not on estimated soil moisture conditions, as is the PDSI, the SPI is just as effective during the winter months. Finally, because of the normal distribution of SPI values, the frequencies of extreme and severe drought classifications for any location and any time scale are consistent. The SPI can be easily related to probabilities of failure and return periods of drought events.

4. Proposed Methodology

The proposed methodology is based on the assumption that a precipitation index as SPI can represent the state of drought at a given location around each meteorological station which is used.

The first step is to reach a spatial distribution of precipitation using monthly values throughout the geographical area under study. Therefore a mesh of square units is used to represent the geographical area. The size of each square unit is selected according to the elevation distribution of the terrain, the uniformity of land cover, the distribution of economic activities, the land use and the size of the area under study, in such a way, so that each square unit represents a uniform portion of land. Needless to say that the size of each square is somehow limited by the computation effort needed to process the necessary calculations. In the application presented below, referring to mesoscale dimensions, the size of the squares was selected to be 2×2 km. However, a bigger size could also be selected mainly in case of larger areas under study.

The selection of meteorological stations representing the sources of data follows the procedures of designing a meteorological network. The use of correlation to describe the statistical spatial structure of rainfall was considered and it was associated with the desired accuracy of the network selected (O'Connell *et al.*, 1977; Tsakiris *et al.*, 1997). The selection of each meteorological station in each application is also influenced by other parameters (apart from the distance or area) such as the reliability of the station, its history and significance, and its working condition.

After the meteorological stations are selected, monthly precipitation data can be estimated for ungauged squares in order to cover the entire number of squares with monthly precipitation values.

The simplest procedure for estimating at each square for the required duration is to link its geographical position in relation to the selected meteorological stations as follows:

$$P_i = \frac{P_1 \frac{1}{d_1^2} + P_2 \frac{1}{d_2^2} + \ldots + P_n \frac{1}{d_n^2}}{\frac{1}{d_1^2} + \frac{1}{d_2^2} + \ldots + \frac{1}{d_n^2}} , \tag{2}$$

where

- P_i is the precipitation calculated at the ith square (mm),
- $P_{1,2,\ldots,n}$ are the precipiation depths recorded at the n meteorological stations, which affect the precipitation of the ith square (mm),
- $d_{1,2,\ldots,n}$ are the distances of the ith square from each of the selected n stations.

The estimated precipitation P_i is then corrected for the altitude as follows:

$$P_{i,\text{final}} = P_i + \Delta H \cdot \beta , \tag{3}$$

where

- $P_{i,\text{final}}$ is the corrected precipitation for the square (mm),
- β is the gradient of precipitation with altitude (mm/100 m), and
- ΔH is the difference between the real altitude of the square center (resulting for the digital terrain model) and the nominal altitude resulting from an equation similar to Equation (2) referring to the altitudes.

If β values are calculated from annual data, monthly or seasonal β values can be produced by desegregating techniques, which recognize the pattern of monthly/ seasonal precipitation data.

Once precipitation data have been estimated for all the squares of the region on an appropriate time scale, then the calculations of the SPI and other indices is a matter of a calculating routine made easily with computer spreadsheets. Calculations for all the years of available data are performed and then presented on grid maps, showing clearly the status of the selected period in relation to the prevailing conditions in the area. Three types of maps can represent the status of the corresponding period in a comprehensive way:

(a) Map of distribution of precipitation.
(b) Map showing the percentage of the normal mean precipitation ($\overline{P}_i$).

$$\tilde{P}_i = 100 \frac{P_{i,\text{final}}}{\overline{P}_i} . \tag{4}$$

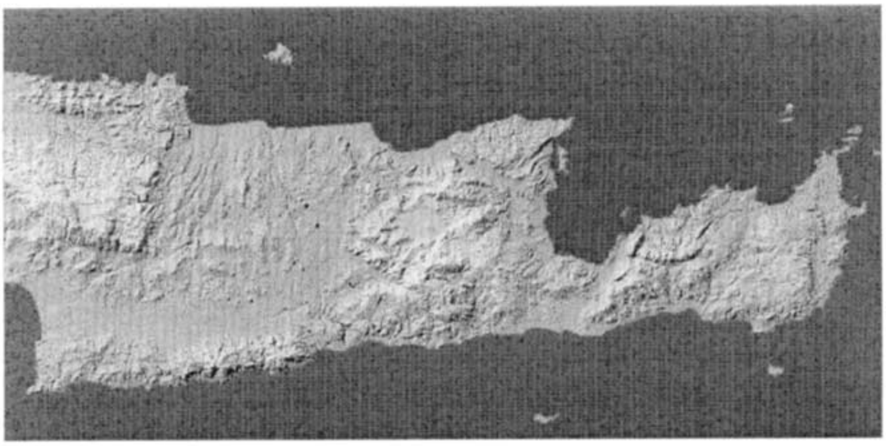

Figure 1. The terrain of Eastern Crete.

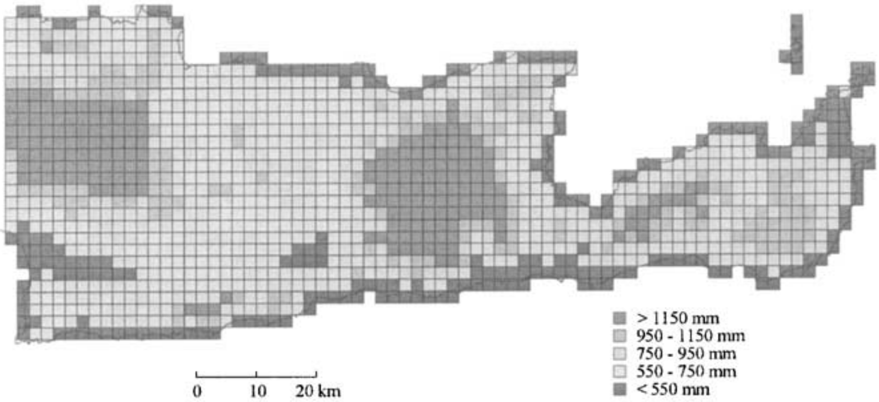

Figure 2. Mean annual distribution of precipitation (period 1962–1992).

(c) Map showing SPI.

It is interesting to note that apart from the presentation of the drought conditions, useful conclusions may be derived for the drought potential of each grid square, by studying the frequence of occurrence of drought level of each square.

5. Application and Discussion

The proposed methodology was applied in mesoscale dimensions. The island of Crete was selected for the application. More precisely the eastern part of the island (about 140 km long) suffering more frequently from droughts, was taken as the geographical area for study. Figure 1 shows the terrain of the area under study, whereas Figure 2 shows the mean annual distribution of precipitation over the period 1962–1992. The area is divided in squares of 2×2 km. A rather dense

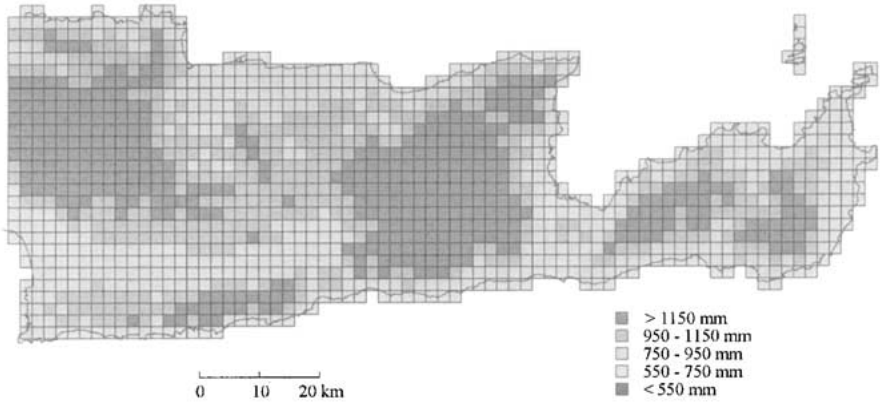

Figure 3. Annual precipitation distribution for 1964–1965.

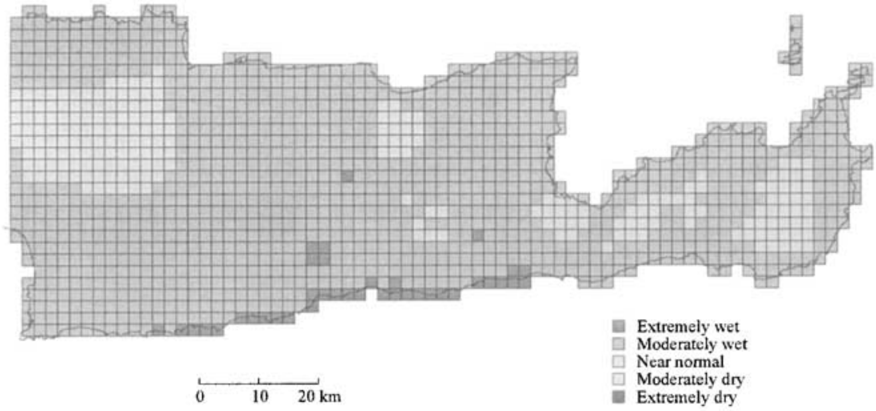

Figure 4. Percentage of normally expected annual precipitation for 1964–1965.

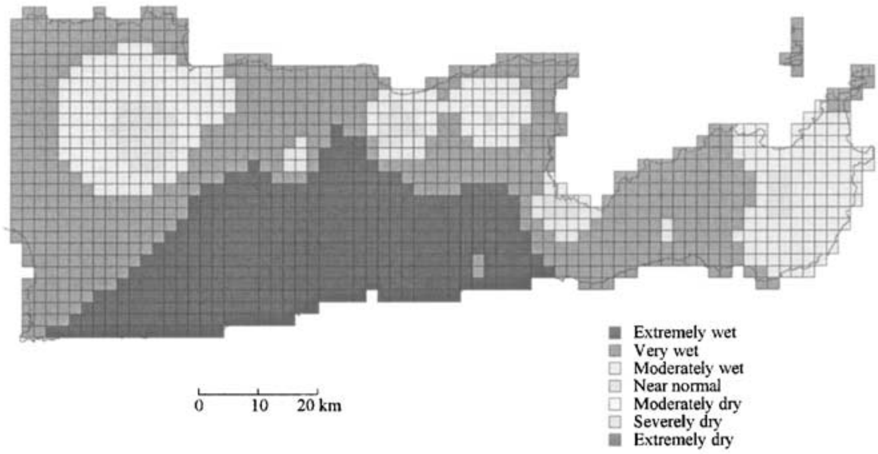

Figure 5. Spatial distribution of SPI for 1964–1965.

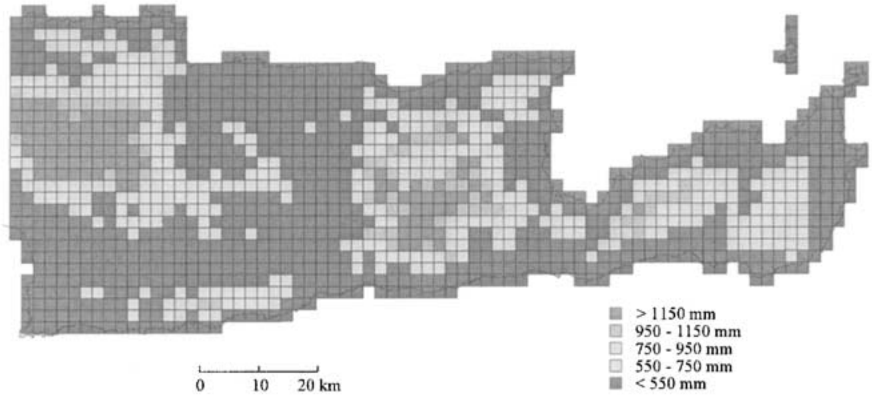

Figure 6. Annual precipitation distribution for 1989–1990.

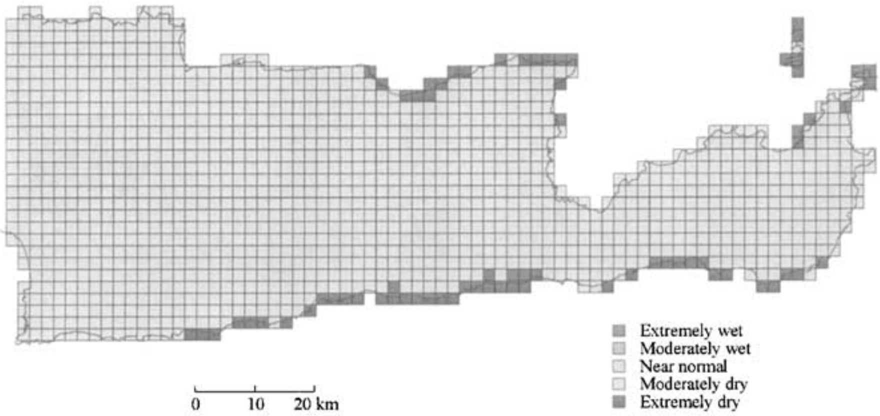

Figure 7. Percentage of normally expected annual precipitation for 1989–1990.

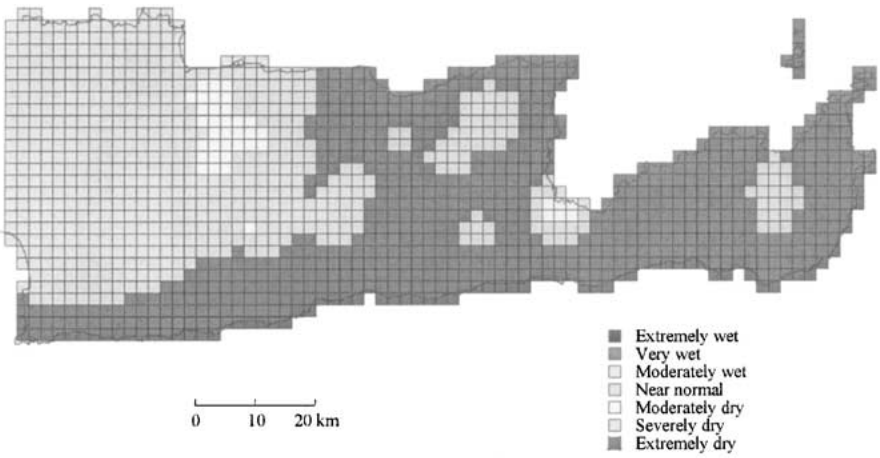

Figure 8. Spatial distribution of SPI for 1989–1990.

meteorological network was used comprising 39 stations distributed all over the area and the altitude.

The results of the analysis of the 3-month, 6-month, and yearly periods were calculated according to the formula presented previously. The results were presented in tables as well as in maps giving visual estimation of the state of drought.

Corrections for the altitude were performed automatically using the digital terrain model of the area.

For illustration purposes three types of maps were presented for all the selected periods. Namely the distribution of precipitation, the percentage of the normally expected precipitation, and the SPI.

In Figures 3, 4 and 5 the above three maps of yearly period are presented for a rather wet year 1964–1965. Similarly Figures 6, 7 and 8 show the same parameters for a dry year such as the year 1989–1990.

By comparing 1964–1965 and 1989–1990 it is easily understood that the latter was a dry year for the area under study. From the above figures and DTM it can be concluded that deviation from the normally expected conditions occur in low altitudes.

It is shown that SPI is a sensitive measure of drought and a statistically understandable index. SPI together with the DTM and the map of precipitation distribution is an easily used index, which can assist a Drought Watch System for an area of mesoscale dimensions.

Finally by studying the sequence of drought events at each square (as described by SPI) the drought potential of each elementary area can be assessed.

6. Concluding Remarks

Using the minimum data requirement approach, it was shown that simple indices such as the SPI with the help of geoinformatics can be used as the basis of a Drought Watch System of an area of mesoscale dimensions, giving straightforward estimations of the severity of drought, its spatial distribution and its duration.

The described procedure can be considered as the first step for assessing regional drought. Needless to say that it should be followed by a more comprehensive approach associated with the anticipated damages caused by drought phenomena, once the proposed simplified procedure has quantified the basic elements of drought. Furthermore, the procedure may be used for assessing the drought potential of each unit area.

The main advantage of the proposed procedure is its simplicity, its transparency and its universality. The results can be produced quickly, with low infrastructure and are understandable and compatible with results from other countries. Therefore the proposed methodology can be an initial basis for devising a Drought Watch System and also the basis for international co-operation of drought estimation and management.

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