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Regional Drought Assessment Based on the Reconnaissance Drought Index (RDI)

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Abstract Regional drought assessment is conventionally based on drought indices for the identification of drought intensity, duration and areal extent. In this study, a new index, the Reconnaissance Drought Index (RDI) is proposed together with the well known Standardized Precipitation Index (SPI) and the method of deciles. The new index exhibits significant advantages over the other indices by including apart from precipitation, an additional meteorological parameter, the potential evapotranspiration. The drought assessment is achieved using the above indices in two river basins, namely Mornos and Nestos basins in Greece. It is concluded that although the RDI generally responds in a similar fashion to the SPI (and to a lesser extent to the deciles), it is more sensitive and suitable in cases of a changing environment.

Key words meteorological drought · drought indices · Reconnaissance Drought Index (RDI) · deciles · SPI · Nestos river basin · Mornos river basin

1 Introduction

Drought is a recurring phenomenon that affects a wide variety of sectors, making it difficult to develop a single definition of drought. According to a water-resource-oriented definition which takes into account the water requirements related to biological, economic and social characteristics of a region, drought refers to a random condition of severe reduction of water supply availability (compared to normal value), extending along a significant period

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of time over a large region (Rossi 2000). It has been pointed out that the criteria to define severe reduction, significant period (duration), and large region are affected by subjectivity, as they stem from the demand level as well as from the perception of negative impacts of the water deficits.

It is generally accepted that drought is a regional phenomenon. However, information is collected by selected meteorological stations, which can be considered as representing the areas attributed to them (e.g., Thiessen polygons). The extent of regional drought is obtained by spatial integration of these areas of influence. The area under drought is then compared to an areal threshold, called "critical area" (Tsakiris et al. 2006).

However, this approach disregards the hydrological processes, which are based on the hydrological basin. For the small basins in particular, it is even more obvious that drought estimation should be referred to the watershed as the unit rather than any other unit area.

Drought indices are important elements of drought monitoring and assessment since they simplify complex interrelationships between many climate and climate-related parameters. Indices make it easier to communicate information about climate anomalies to diverse user audiences and allow scientists to assess quantitatively climate anomalies in terms of their intensity, duration, frequency and spatial extent (Wilhite et al. 2000). This allows the analysis of the historical occurrence of droughts and the estimation of recurrence probability. This information is extremely useful for planning and designing applications of water resources development schemes, related to various uses and the environment.

2 Drought Identification Indices

The Standardized Precipitation Index (SPI), which is one of the most widely used drought indices, was designed by McKee and his colleagues at Colorado State University (McKee et al. 1993). It is based on the consideration that each component of a water resources system reacts to a deficit in precipitation over different time scales.

The SPI has the following favourable characteristics: (a) It is uniquely related to probability; (b) the precipitation used in the SPI can be used to calculate the precipitation deficit for the current period and the current percent of average precipitation for a time period of i months and (c) the SPI is normally distributed so it can be used to monitor wet as well as dry periods.

Another widely used meteorological index is the rainfall deciles, which was developed by Gibbs and Maher (1967). The index divides the distribution of occurrences over a long-term precipitation record into tenths of the distribution. Each of these categories is called a *decile*. If the sum falls within the lowest decile of the historical distribution of 3-month totals, then the region is considered to be under drought conditions. The drought ends when (a) the precipitation measured during the past month already places the 3-month total in or above the fourth decile, or (b) the precipitation total for the past 3 months is in or above the eighth decile (Kinninmonth et al. 2000).

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

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

3 The Reconnaissance Drought Index (RDI)

After a systematic study of the various indices applied to identify and assess the meteorological drought severity it was concluded that although all these indices were useful, none of them seemed to attract universal applicability. Nevertheless, during the last decade the SPI has become very popular due to its low data requirements.

A new reconnaissance drought identification and assessment index was first presented in the coordinating meeting of MEDROPLAN (Tsakiris 2004), while, a more comprehensive description was presented in other publications (Tsakiris and Vangelis 2005; Tsakiris et al. 2006).

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

$$\alpha_0^{(i)} = \frac{\sum_{j=1}^{12} P_{ij}}{\sum_{j=1}^{12} PET_{ij}}, \mathrm{i} = 1(1)\mathrm{N}\,\mathrm{and}\,\mathrm{j} = 1(1)12 \tag{1}$$

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

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

$$RDI_n^{(i)} = \frac{\alpha_o^{(i)}}{\overline{\alpha}_o} - 1 \tag{2}$$

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

$$RDI_{st(k)}^{(i)} = \frac{y_k^{(i)} - \overline{y}_k}{\widehat{\sigma}_{y_k}} \tag{3}$$

in which y_i is the ln $\left(\alpha_o^{(i)}\right), \overline{y}_k$ is its arithmetic mean and $\widehat{\sigma}_{y_k}$ is its standard deviation.

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

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

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

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

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

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

It should be mentioned that usually droughts in the Mediterranean are accompanied by high temperatures, which lead to higher evapotranspiration rates. Evidence for this has been produced from simultaneous monthly data of precipitation and evapotranspiration in many Greek watersheds. From the cases analyzed it seems that about 90% of them comply with the previous statement (Tsakiris and Vangelis 2005). Therefore, the RDI is expected to be more sensitive index than those related only to precipitation, such as the SPI.

The RDI can be calculated for any period of time from 1 month to the entire year, even starting from a month different than October, which is customary for the Mediterranean. Very significant results can be derived if the period of analysis coincides with the growing season of the main crops of the area under study or other periods related to sensitive stages of crop growth. Then, the RDI can be associated successfully with the expected loss in rainfed crop production, which in turn is linked to the anticipated hazard in the agricultural sector due to drought occurrence.

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

Likewise, PET may be a representative quantity of the consumption in various sectors apart from agriculture. Water demand is increasing in general in case of higher temperatures. Therefore, the RDI could be modified to be used in the future as an indicator for the drought risk assessment related to the various sectors of water use.

4 Case Study 1: The Mornos Basin

The Mornos river basin is located in central Greece. The entire basin occupies an area of 1,025 km^2, while the study area covers 571 km^2. The latter area is the watershed of the river at the site of a dam, which was constructed in the late 70s to supply Athens greater area with potable water.

The study area is very mountainous, with a mean altitude of 1,020 m. The parent rock is flysch and limestone, and the soils are clay loam and loam.

The mean annual precipitation of the watershed is 1,140 mm ranging from 863 mm (Lidoriki station, altitude 537 m) to 1,360 mm (Pyra station, altitude 1,140 m). Precipitation is measured at eight stations, which have been in operation for more than 40 years. The data used for this study are from the period 1962–2001. The mean annual PET, calculated using the Penman method, as it was modified by Doorenbos and Pruitt (1977) varies between 1,229 mm (Pyra station) and 1,348 mm (Lidoriki station).

According to the FAO aridity index, the area under study can be characterized as humid.

The Run Method was applied to calculate the regional water deficits for the period and the area under study, based on precipitation. The results from the run method are presented in Figure 1, in which the selected meteorological stations and the corresponding Thiessen polygons also appear.

The maximum deficit is observed at Pentagi station during the years 1987–1995 (3,449 mm). This is also the most severe drought spell, as it lasted for 8 consecutive years. However, the maximum annual drought intensity is observed in the same station for the hydrological year 2000–2001 (557.5 mm/year), whereas for the period 1987–1995 the average drought intensity was 431.1 mm/year.

Figure 2 presents the influence of the polygons to the entire basin through the hydrological time series. It is obvious that since 1987 in most of the years, the Mornos basin suffers from droughts.

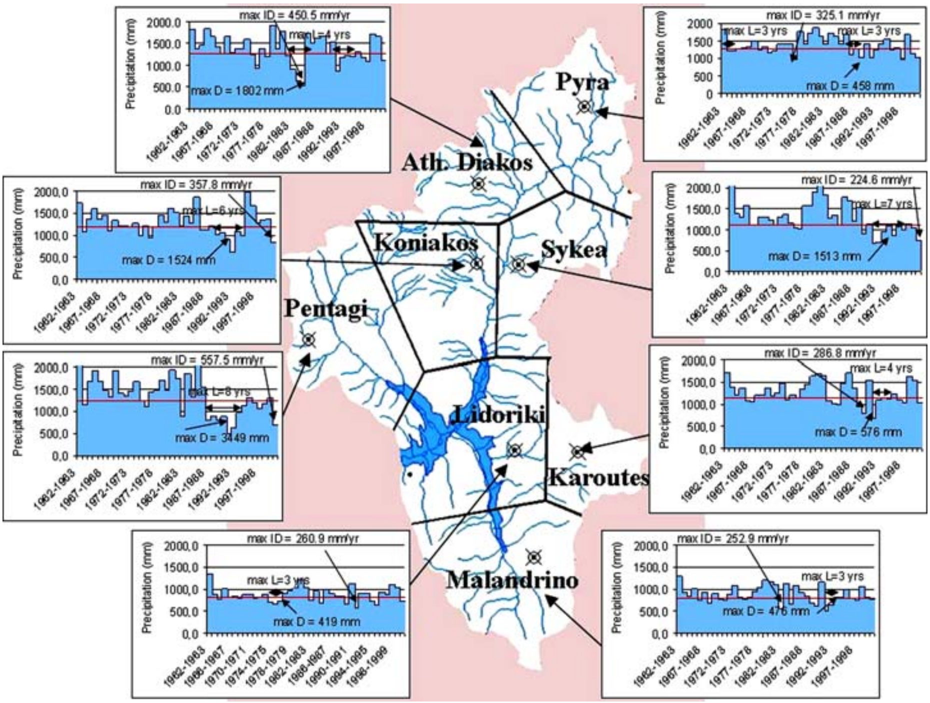


Figure 1 Droughts identified on hydrological series on each station of the Mornos basin and their characteristics.

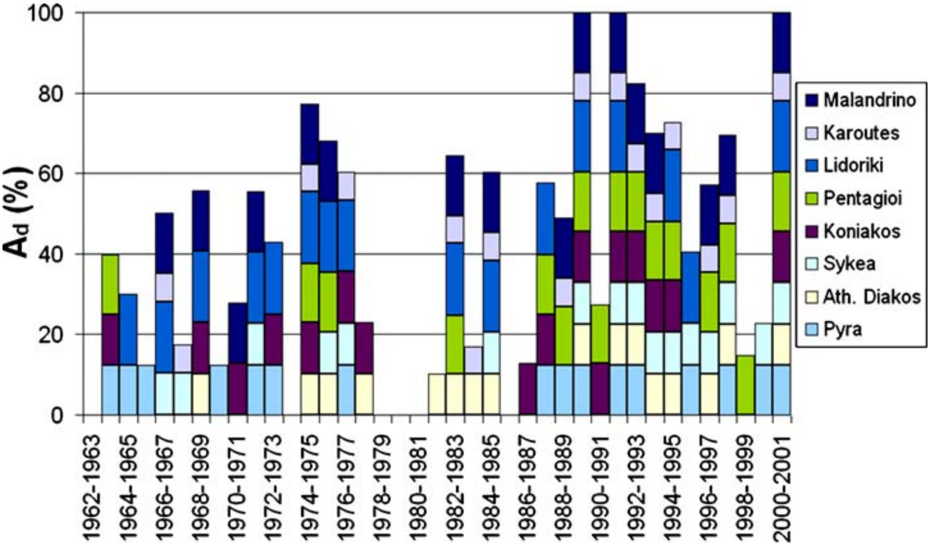


Figure 2 Regional drought identification for the Mornos basin.

The critical area A_{crit} was considered equal to 25% of the basin. The water deficits along the whole basin are shown in Figure 3, according to the theory of runs.

For the needs of the study, the drought indices, SPI, deciles and RDI, were calculated following the standard procedure. The drought indices were also calculated for the total basin using Thiessen polygons and appear in Figure 4. From these figures, one can assume that all indices behave in more or less similar way.

Correlations between the RDI and the other two indices seem to be satisfactorily. The linear correlation coefficient between the RDI and the Deciles was found 0.90, whereas the

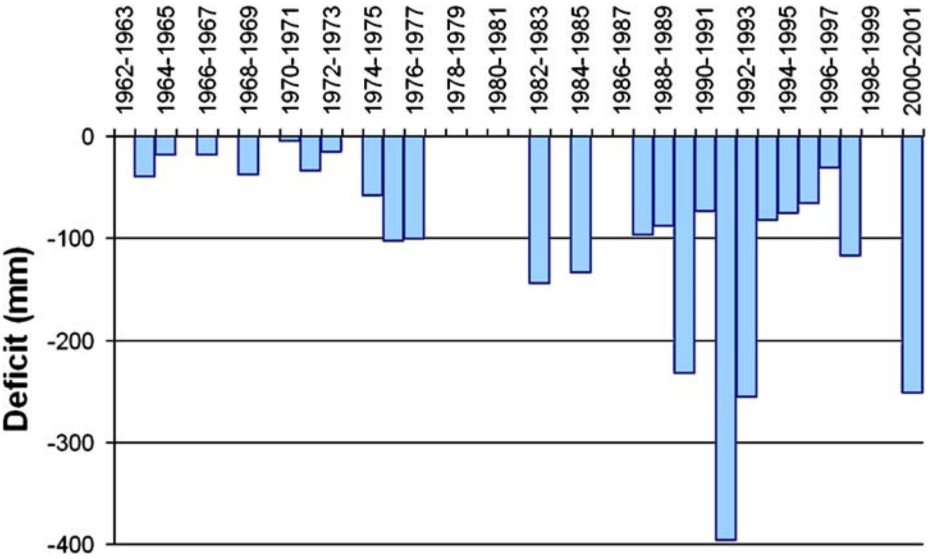
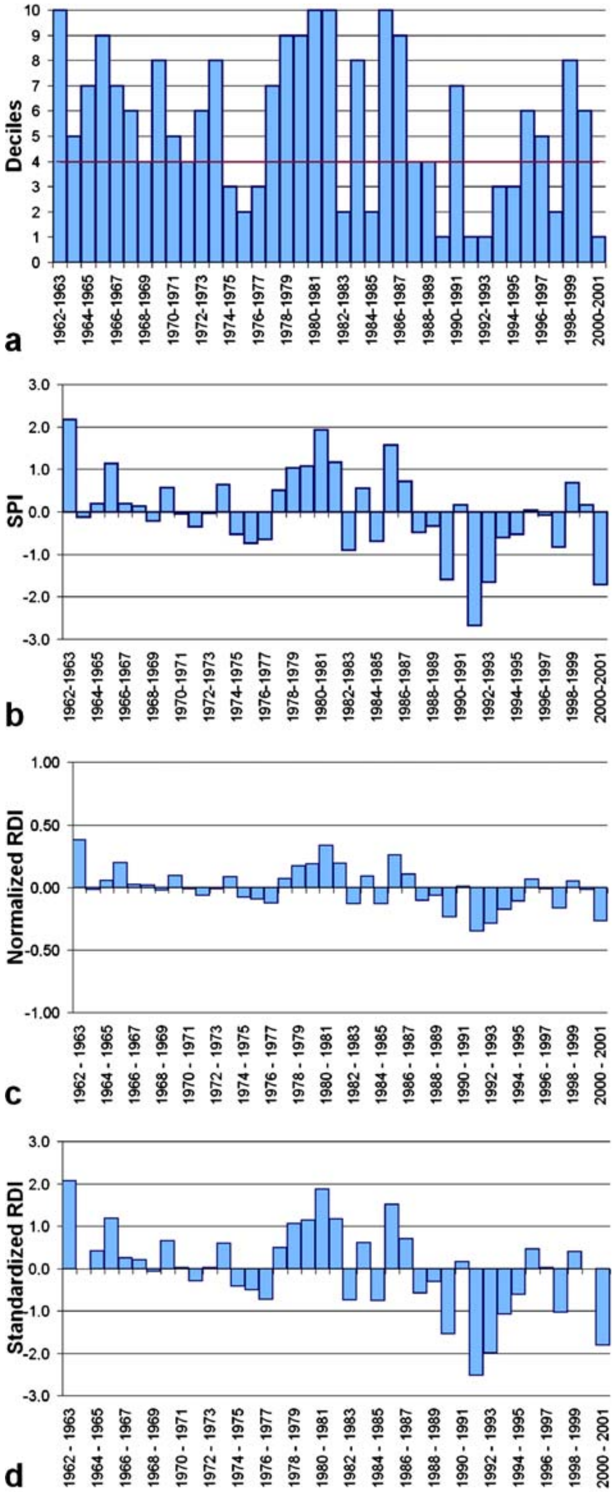


Figure 3 Deficit during drought periods for the Mornos basin.

Figure 4 Annual Drought Identification for Mornos Basin. **a** Deciles. **b** SPI. **c** Normalized RDI. **d** Standardized RDI.



same coefficient between the RDI and the SPI was equal to 0.98. This is most probably due to the very small variability of annual PET that was reported earlier in this text. However, if Figure 4b and d are compared it can be concluded that slight differences can be observed between the values of the RDI and the SPI.

5 Case Study 2: The Nestos Basin

The Mesta-Nestos is a cross-border basin between Bulgaria and Greece. The entire basin of Mesta-Nestos is 5.751 km^2 with 2.314 km^2 lying in Greece and the rest in the Bulgarian territory. The study presented here refers to the Greek part of the basin.

The topography of the main part of the Nestos catchment is an alternating sequence of valleys and ridges, except in the Nestos Delta plain. As far as the geology of the catchment area is concerned, the mountainous part of the Nestos basin consists of metamorphic rocks (marbles, gneisses, schists), igneous rocks and deposits of quaternary to recent age.

The mean annual precipitation of the study area is 864 mm and ranges from 544 mm (at Chryssoupoli station) to 969 mm (at Sidironero station), during the period 1962–1996. The monthly precipitation and temperature data are available in 10 stations within the basin. The mean annual PET, calculated by Penman method, varies from 660 mm (Sidironero station) to 820 mm (Chryssoupoli station).

According to the FAO Aridity index, the basin can be considered as humid in the north and sub-humid in the south.

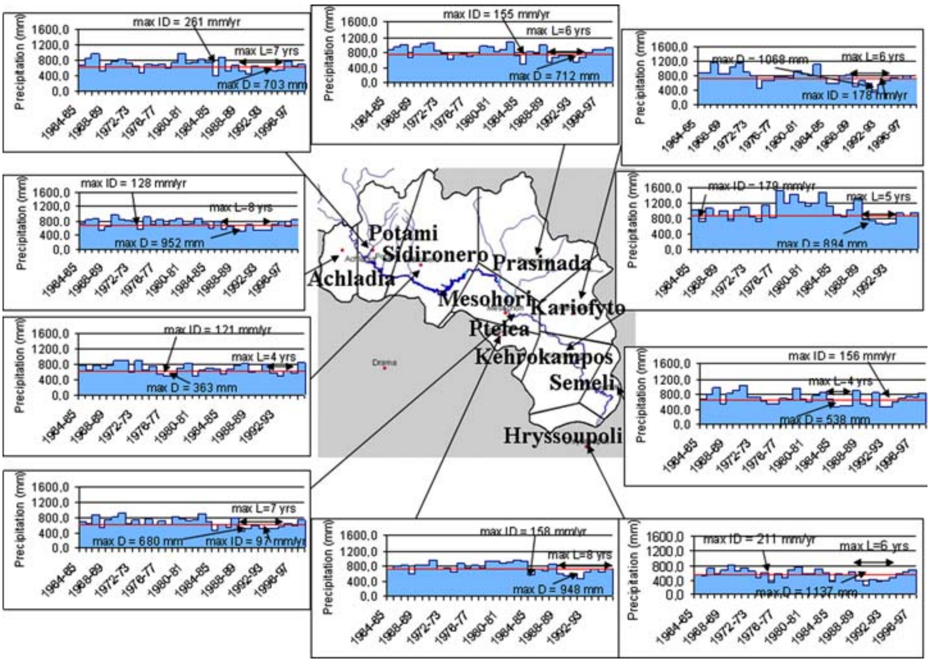


Figure 5 Droughts identified on hydrological series on each station of the Nestos watershed and their characteristics.

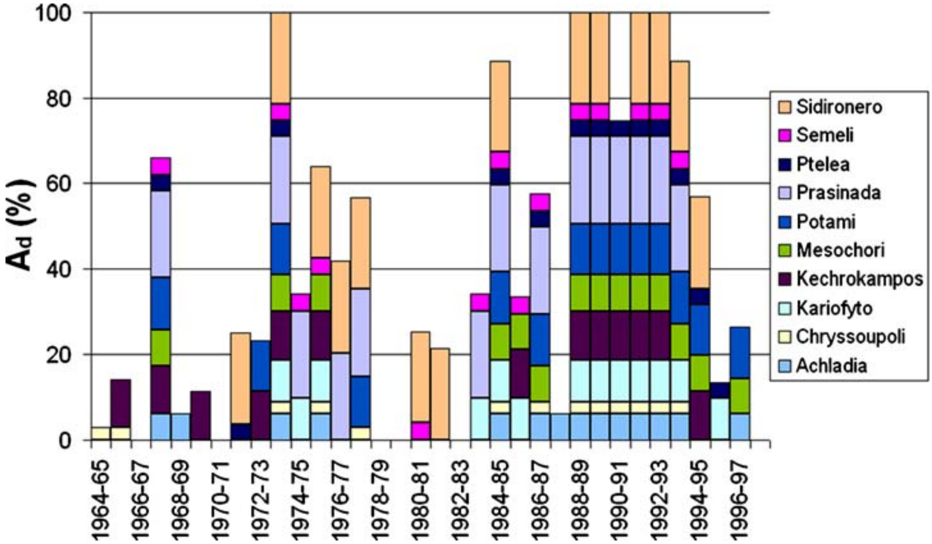


Figure 6 Regional drought identification for the Nestos watershed.

Following the same methodology, Figures 5, 6 and 7 are presented, showing the results of the run method, the percentage of the area under drought and the deficit during the drought occurrence for the area under study during the period 1964–1998.

In Figure 5, the basin is divided into Thiessen polygons and the results of the run method for all the stations are presented.

The maximum deficit is observed at Hryssoupoli station during the years 1988–1994 (1,137 mm). The greater drought spell lasted for 8 years, and it affected both the stations of Achladia and Ptelea for the years 1986–1994 and 1988–1996 respectively. However, the

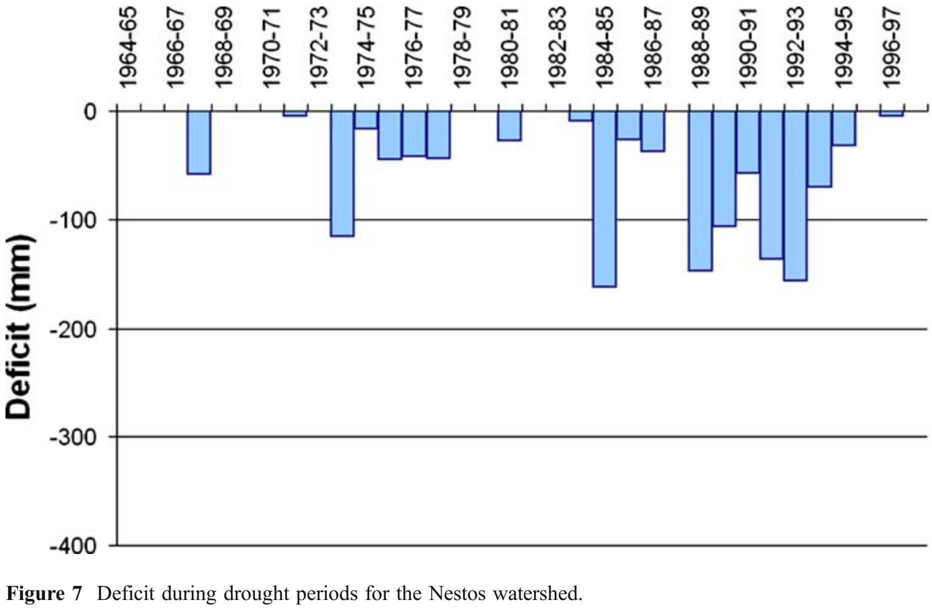
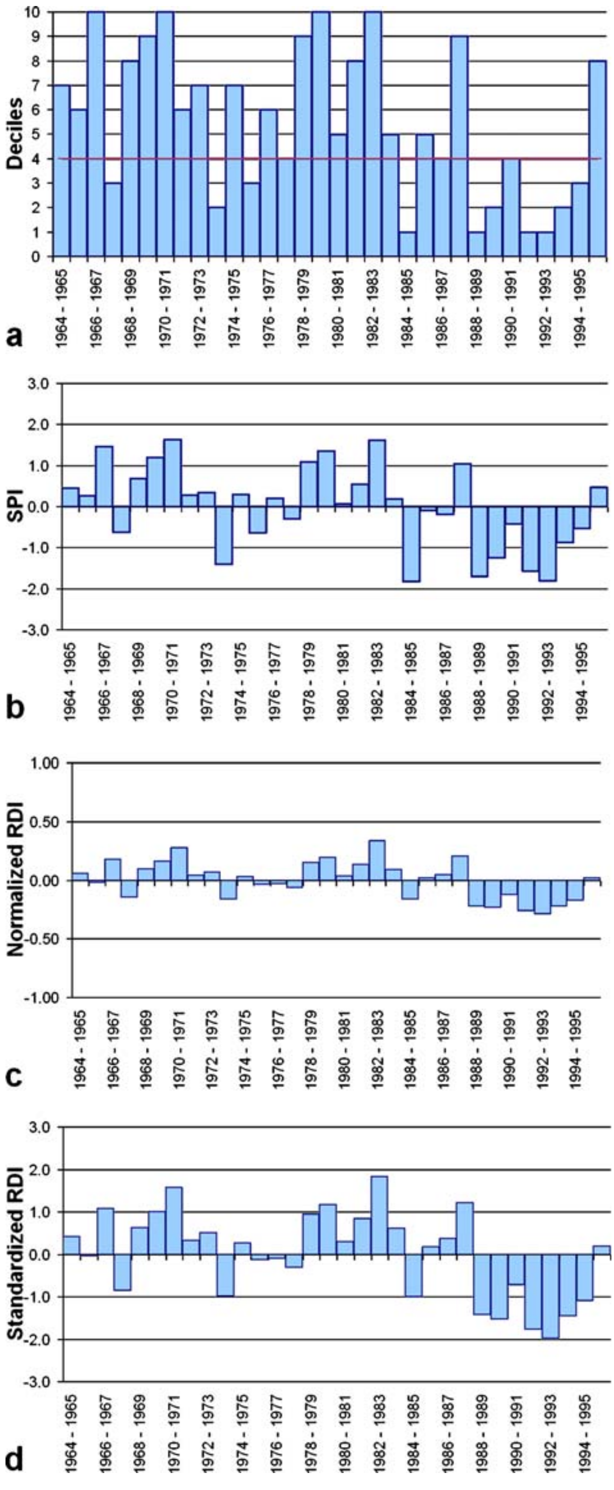


Figure 7 Deficit during drought periods for the Nestos watershed.

Figure 8 Annual drought identification for Nestos Basin. **a** Deciles. **b** SPI. **c** Normalized RDI. **d** Standardized RDI.



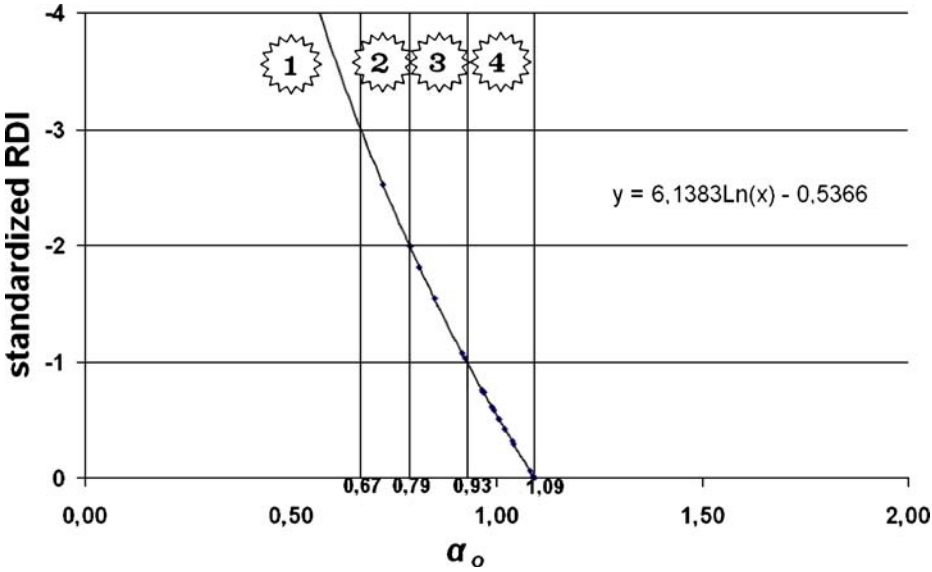


Figure 9 Establishing the levels of drought for α_o for the Mornos basin.

maximum drought intensity was observed at the Potami station but for the hydrological year 1984–1985 (261.5 mm/year).

The drought indices (deciles, SPI, RDI) were calculated for the mean altitude of the basin (760 mm) as well as for every station of the basin, using Thiessen polygons. Figure 8 presents the evolution of drought indices for the basin for the period 1964–1965 to 1994–1995.

Statistical measures of the agreement between the various drought indices show that although they do not result in the same figures they behave more or less in the same

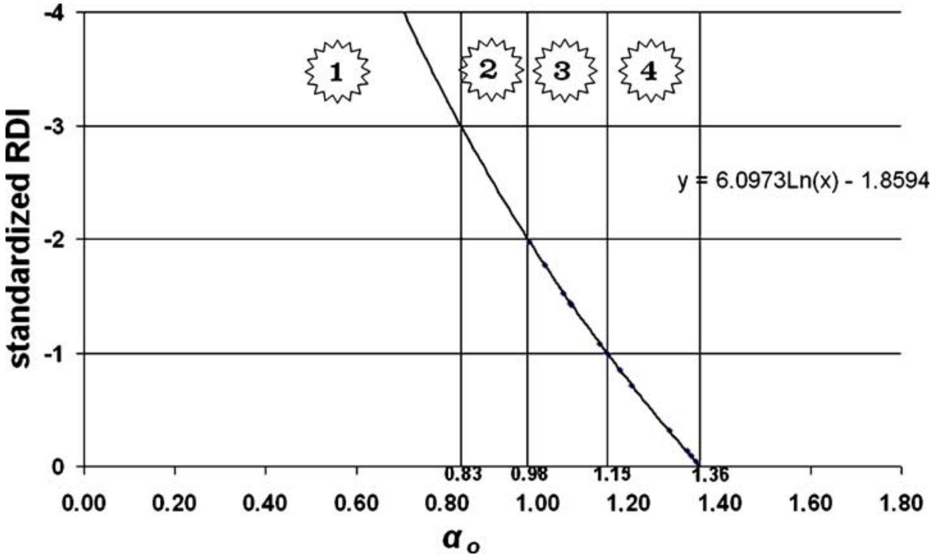


Figure 10 Establishing the levels of drought for α_o for the Nestos basin.

manner. Differences between the SPI and the standardized RDI may be attributed to the additional meteorological parameter (PET) used for the calculation of the RDI.

As in the case of Mornos basin the standardized RDI correlates satisfactorily to the Deciles and the SPI in the Nestos basin. The correlation coefficient between the RDI and the Deciles is equal to 0.87 and between the RDI and the SPI is equal to 0.90.

6 Discussion and Concluding Remarks

The parameter "demand of the atmosphere" is represented by the PET of the reference crop as proposed by Penman (Allen et al. 1997) or just reference crop evapotranspiration (Monteith 1981). PET may be also calculated by other empirical methods in an attempt to minimize the data required. The popular Thornthwaite method or the Blaney–Criddle method seem to be suitable for the Mediterranean region. Monthly PET, according to the Thornthwaite method, is based only on mean air temperature data and the latitude of the location, which are available for most locations around the globe.

According to studies carried out for the Mediterranean region, Thornthwaite PET can be transformed to Penman's PET. Linear regression functions have been proposed for this transformation (Picatoste et al. 1998).

The potential evapotranspiration however, as a "demand factor", is inclined to represent water consuming activities, mainly associated with the predominant agricultural sector. Although this is true for most of the Mediterranean areas (consumption of water in agriculture is between 70% and 90% of the total consumption), there are cases in which municipal or tourist consumption is also significant. For those cases, provision should be included to correct PET by appending an additional percentage to represent the extra water consumption for other uses.

The calculation of the standardized RDI seems to be as complicated as the computation of the SPI. However, once this calculation is completed for a certain area, then the thresholds are defined for using α_o or RDI_n, which can be calculated easily.

If the levels of drought for the α_o are needed and there is no better way to calculate them (e.g., anticipated damage), they can be produced by being expressed as the corresponding values of the levels − 1, − 2 and − 3 of the standardized RDI. This is clearly shown in Figures 9 and 10. In these figures, which apply for the data of Mornos and the Nestos basins respectively, the corresponding values of α_o to the above limits are 0.93, 0.79 and 0.67 for the Mornos case and 1.05, 0.98 and 0.83 for the Nestos case (for values − 1, − 2 and − 3 of standardized RDI). Thus, the levels of severity of droughts are shown in Figures 9 and 10 as ①,②,③ and ④.

Therefore, once the levels of drought for the α_o are established, the assessment of severity of drought can be assessed by comparing α_o for the year under question to the thresholds calculated for the area.

In a more comprehensive way, the thresholds of the severity of drought should be based not on a quantity derived from probability function such as the standardized variate but on the anticipated impacts caused by drought to the various sectors of the economy, to the socio-economic system and the environment, affected by drought. However, if such historical data are not available, empirically determined Loss functions may be also used.

An important issue, which should be further studied is the multiyear drought impacts. This issue should be related and studied through the vulnerability of the systems at risk.

From the analysis presented in this paper, it may be concluded that the recently proposed Reconnaissance Drought Index (RDI) has many advantages over the widely used indices for assessing meteorological drought. Although it seems that in the majority of cases it responds similarly to the SPI and in accordance with the deciles, it is expected to be a more sensitive and more comprehensive index for comparisons of drought conditions between different parts of the world. Obviously this may be due to the fact that the SPI and the Deciles are less demanding data methods.

According to the Models of General Circulation (MGC) anticipated climate change in the Eastern Mediterranean involves both decrease of precipitation and increase of potential evapotranspiration. Therefore, the RDI seems to be a more reliable index to assess droughts in a changing climatic environment.

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References

Allen RG, Pereira LS, Raes D, Smith M (1997) Crop evapotranspiration, Guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper No. 56

Ben-Zvi A (1987) Indices of hydrological drought in Israel. J Hydrol 92:179–191

Clausen B, Pearson CP (1995) Regional frequency analysis of annual maximum streamflow drought. J Hydrol 173:111–130

Correia FN, Santos MA, Rodrigues R (1987) Engineering risk in regional drought studies. In: Duckstein L, Plate EJ (eds) Engineering reliability and risk in water resources. Martinus Nijhoff, Dordrecht

Doorenbos and Pruitt (1977) Guidelines for predicting crop water requirement. FAO Irrigation and Drainage Paper No. 24, FAO, Rome. pp 34–37

Gibbs WJ, Maher JV (1967) Rainfall deciles as drought indicators. Bureau of Meteorology Bulletin 48, Commonwealth of Australia, Melbourne

Kinninmonth WR, Voice ME, Beard GS, de Hoedt GC, Mullen CE (2000) Australian climate services for drought management. In: Wilhite DA (ed) Drought: A global assessment. Routledge, London

McKee TB, Doesken NJ, Kleist J (1993) The relationship of drought frequency and duration to time scales. Proceedings of the 8th Conference on Applied Climatology; 17–22 January 1993, American Meteorological Society, Boston

Monteith JL (1981) Evaporation and surface temperature. Q J R Meteorol Soc 107:1–27

Picatoste JR, del Hoyo J, Pallares MA, Moreno T (1998) Aridity map of Spain. In: N. Dalezios (ed) Proceedings of the International Symposium of Applied Agrometeorology and Agroclimatology. pp 475–480

Rossi G (2000) Drought mitigation measures: a comprehensive framework. In: Voght JV, Somma F (eds) Drought and drought mitigation in Europe. Kluwer, Dordrecht

Rossi G, Benedini M, Tsakiris G, Giakoumakis S (1992) On regional drought estimation and analysis. Water Resour Manag 6:249–277

Tsakiris G (2004) Meteorological Drought Assessment. Paper prepared for the needs of the European Research Program MEDROPLAN (Mediterranean Drought Preparedness and Mitigation Planning), Zaragoza, Spain

Tsakiris G, Vangelis H (2005) Establishing a drought index incorporating evapotranspiration. Eur Water 9–10:1–9

Tsakiris G, Rossi G, Iglesias A, Tsiourtis N, Garrote L, Cancelliere A (2006) Drought Indicators Report. Report made for the needs of the European Research Program MEDROPLAN (Mediterranean Drought Preparedness and Mitigation Planning)

Wilhite DA, Hayes MJ, Svodoba MD (2000) Drought monitoring and assessment in the U.S. In: Voght JV, Somma F (eds) Drought and drought mitigation in Europe. Kluwers, Dordrecht

Yevjevich V (1967) An objective approach to definitions and investigations of continental hydrologic drought. Hydrology Paper No. 23, Colorado State University, Colorado

Yevjevich V, Da Cunha L, Vlachos E (1983) Coping with droughts. Water Resources Publications, Littleton, Colorado

Zelenhasic E, Salvai A (1987) A method of streamflow drought analysis. Water Resour Res 23(1):156–168