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Uni-dimensional Analysis of Droughts for Management Decisions

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Abstract: Drought is a three-dimensional recurrent phenomenon (severity, duration, areal extent) which is difficult to model for management decisions. The paper proposes a number of simplifications for replacing the three dimensions by a unique dimension in an attempt to devise a practical methodology, which can assist decision makers and stakeholders to face droughts during both the planning and the operational management phase. To obtain this simplification the river basin or sub-basin is used as the territorial unit for the drought analysis, whereas, the reference period is introduced for replacing the duration of the drought events on the temporal scale. Drought severity is represented by the Reconnaissance Drought Index (RDI) and supplementarily by the Standardized Precipitation Index (SPI). The proposed simplified methodology is illustrated by presenting examples from the real world.

Keywords: Drought, river basin, drought management, drought indices, RDI, SPI

1. INTRODUCTION

Drought is a recurring natural regional phenomenon associated with severe reduction of water supply availability (compared to normal value) extending along a significant period of time over a large area. From this definition, it is easily concluded that for frequency analysis of droughts three dimensions should be modelled and studied: the severity, the duration and the areal extent.

It is customary to characterise drought using drought severity indices which are special combinations of meteorological, hydrological or other indicators. Drought indices provide representations of historical droughts and therefore place current conditions in historical perspective. They are valuable for planning and management purposes for providing decision makers with a measure of negative deviation from normal conditions of water availability.

Among the various indices, the most popular are those of general meteorological type. Numerous indices have been proposed and used over the last decades. The Palmer Drought Severity Index (PDSI) (Palmer, 1965), which is based on a simplified soil water balance model, and the Standardized Drought Index (SPI) (McKee et al., 1993), which is based on precipitation are those which have been extensively used worldwide. Recently, a new promising drought severity index of similar nature as the SPI, the Reconnaissance Drought Index (RDI) was proposed and used successfully in a number of Mediterranean countries (Tsakiris and Vangelis, 2005; Tsakiris et al., 2007a). RDI is based on the ratio of cumulative precipitation and potential evapotranspiration values. Three expressions of RDI are used; the initial, the normalised and the standardised. The last uses similar rules and thresholds with SPI. Analytical reviews on the subject give detailed descriptions of most drought indices whereas specific software (e.g. DrinC) have been written for their calculation (Tsakiris and Pangalou, 2009; Tsakiris et al., 2007b).

It is easily understood that adoption of the three dimensional modelling of droughts creates a complicated process for its frequency analysis and assessment of impacts. For this reason it is very difficult to be used by water managers for management decisions. Needless to say that water managers should take decisions in case of drought occurrence in a quick, robust and transparent way convincing stakeholders that the decisions are correct and appropriate. By adopting a single dimension and a single drought severity index, a firm ground is created for transparent decisions of corporate bodies including authorities, stakeholders and the public.

The objective of this paper is to present a framework that conceptualises adoption of a uni-dimensional approach for the analysis and assessment of drought episodes.

2. THE METHODOLOGY: FROM THREE TO ONE DIMENSION

This paragraph describes the attempt to replace the duration, the areal extent and the severity of a drought episode by only one indicator, therefore analysing droughts as uni-dimensional phenomena.

2.1 Duration

Duration of a drought event is usually measured in days or months from the onset to the termination of the event. Experience has shown that neither the beginning nor the end of drought can be clearly determined. Also, there might be cases in which one month is dry (below average) and the next month is wet (above average) so that in practice no distinct duration can be estimated. To overcome this problem, duration is not considered directly as a drought determinant. Instead, a preset period the "reference period" is proposed in which the meteorological and/or hydrological variable values are referred to. Therefore, if the beginning of the hydrological year is fixed (e.g. 1 October for the Mediterranean region), the 3-month, 6-month, 9-month and 12-month periods could be selected for assessing the conditions and characterise each of the above periods. The major advantage of these reference periods (all starting from the same date) is that monitoring of drought has a firm standard temporal reference and comparisons of drought conditions between different locations are highly facilitated.

Further the selected aggregated periods facilitate the analysis of drought avoiding separate severity assessment for each time step (1 month or 3 month periods) and then aggregation.

2.2 Areal Extent

The second dimension which is proposed to be replaced is the areal extent of drought. Conventionally, information on meteorological variables is collected at selected meteorological stations. These stations can be considered as representing the areas of influence (e.g. Thiessen polygons). According to the conventional estimation of drought extent the drought affected areas are aggregated and their percentage toward the total area under study is compared with the "critical area percentage". Drought is considered significant if the affected area percentage is greater than a preset critical area percentage.

The described procedure, although it may give detailed information on the spatial extent of drought, has some serious drawbacks mainly as regards to the decision making:

i. The critical area percentage is arbitrary leaving decision makers without a rational procedure for its determination.
ii. The critical area approach neglects the natural processes such as the rainfall-runoff process, which is realized within each river basin.
iii. The above approach does not refer to the management unit, which is the river basin. As known the river basin (or a compound of adjacent small river basins) is the territorial unit on which management decisions related to water resources should be taken according to the EU Water Framework Directive 2000/60.

In order to overcome these drawbacks, the following simplified procedure is proposed for replacing the areal extent by the river basin area:

a. The meteorological data are transferred from the meteorological stations to the basin level taking into account the area of influence of each meteorological station in the area.

b. Altitude correction is performed so that the spatial average represents the true mean altitude of the basin.
c. The selected drought severity index is calculated using the data transferred at the basin level.

It should be mentioned that the calculation of the selected drought index at each meteorological station and then its transfer to the mean basin level should be avoided due to the non-linearity of these processes.

2.3 Drought Severity Index

The above type of simplification is more robust if the selected drought severity index is of an aggregated type such as the recently proposed Reconnaissance Drought Index, RDI. As was mentioned earlier, RDI is based on the cumulative precipitation and potential evapotranspiration. RDI can be expressed in three forms: the initial value, the normalised RDI and the standardised RDI. Detailed description of RDI may be found in other papers (Tsakiris and Vangelis, 2005; Tsakiris et al., 2007a).

The adoption of the standardized RDI may be directly interpreted in terms of the "Return Period", which is a popular concept for engineers and authorities from the selected area of Flood Engineering and Management. Therefore, if the above mentioned reference periods (3, 6, 9 and 12 months) are adopted, we could obtain for the Mediterranean RDI_3 (Oct-Nov-Dec), RDI_6 (Oct-March), RDI_9 (Oct-June) and RDI_{12} (Oct-Sept). It should not be forgotten that the initial value of RDI_{12} can be directly compared with the FAO Aridity Index of the area, which characterises the climate of the area under study.

Using the above reference periods, historical data of droughts could be stored and possible trends could be investigated. Also by selecting a drought index which is based on cumulative values of meteorological parameters in practice we overcome the necessity of using transition probabilities from one period to the next as it is the procedure followed for the incremental approaches.

Regarding the monitoring of drought, if for the first trimester RDI is negative then a more systematic monthly monitoring should be initiated. Therefore, the RDI is calculated for reference periods starting from 3 months to 12 months with one month increment (e.g. 3, 4, 5 months, etc.)

As mentioned, RDI_{st} and SPI use the same thresholds for characterising droughts. These thresholds appear in Table 1.

Following the above simplifications and selecting a unique drought severity index, decision makers have a unique drought assessment, which can be correlated effectively with the streamflow or the water reserves within the river basin.

The use of SPI as additional drought index secures that the procedure can be followed even in the case of having only precipitation data. Anyhow SPI is used not as a "rolling" index of constant duration but as a substitute of RDI referring to the selected reference periods.

Table 1. Drought categories based on RDI.

Extremely wet	> 2.00
Very wet	1.50 to 1.99
Moderately wet	1.00 to 1.49
Near Normal	-0.99 to 0.99
Moderately dry	-1.00 to -1.49
Severely dry	-1.50 to -1.99
Extremely dry	< -2

3. APPLICATIONS

3.1 Linking meteorological with the hydrological drought

The case of three small river basins in Northern Peloponnese was studied for assessing the impact of droughts and climate change scenarios on the streamflow. The river basins studied are of the rivers Krathis, Krios, and Sithas.

Some geomorphological characteristics are presented in Table 2.

Table2. Geomorphological characteristics of Krathis, Krios and Sythas river basins.

River Basin	**Area A (km^2)**	**Perimeter P (km)**	**Mean Altitude H_m (m asl)**	**River Length L (km)**	**Hydrographic Density D (km/km^2)**
Krathis	1453.0	74.9	+1105.5	33.0	2.31
Krios	112.7	55.9	+1015.0	23.5	1.89
Sythas	164.3	72.5	+ 960.8	35.5	2.90

Streamflow data were calculated through the application of models which were calibrated by a series of measurements in situ. Two simple conceptual models, the Medbasin (daily) (Tigkas and Tsakiris, 2004) and the SWBM (monthly) (Giakoumakis et al., 1991) were found to be suitable and in agreement with each other and with the available data. Annual streamflow data appear in Figure 1 and Figure 2 for the three rivers by using annual series and Box-Whisker plots.

The reference period is considered as the entire hydrological year (Oct. – Sept.) for the calculation of drought index RDI. In Table 3 the reduction in annual streamflow is calculated using the models Medbasin and SWBM, based on a number of scenarios of precipitation reduction and potential evapotranspiration increase, which are also represented by the annual standardized RDI_{12}.

It should be clarified that RDI_{12} is calculated using data averaged at the entire basin of each river. Precipitation and temperature from the meteorological stations of the area were transferred to the basin scale using the Thiessen's polygon method followed by altitude correction.

Table 3, therefore, presents a uni-dimensional drought severity assessment corresponding to annual reference period (instead of duration) and the entire basin of each river (instead of areal extent).

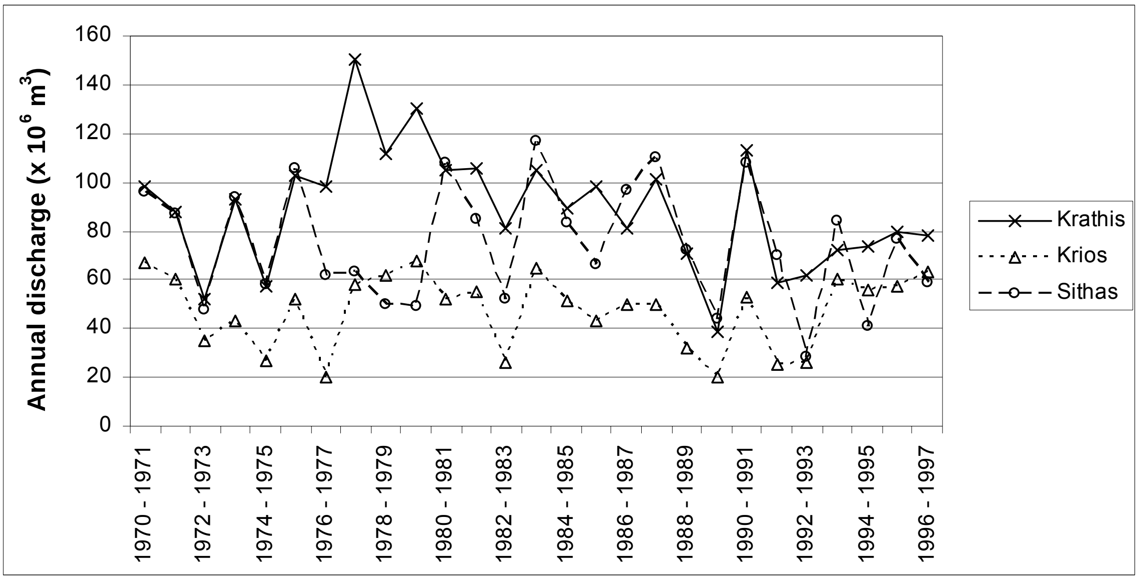

Figure 1. Annual Streamflow data series (1970/71 - 1996/97) for the rivers Krathis, Krios and Sythas.

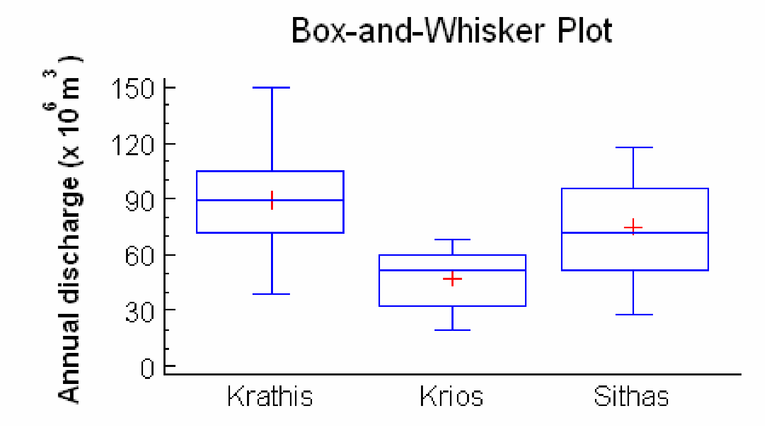

Figure 2. Box-Whisker plots for streamflow data of the rivers Krathis, Krios and Sythas.

Table 3. Annual streamflow reduction related to the changes of meteorological variables and the annual standardised RDI.

River basin	Precipitation reduction (%)	PET increase (%)	RDI_{12}	Streamflow reduction (%)
Krathis	6.0	4.0	-0.41	8.8
	14.0	6.0	-1.00	19.5
	20.0	10.0	-1.59	27.8
	26.0	14.0	-2.21	36.0
	36.0	18.0	-3.18	48.8
Krios	6.0	4.0	-0.44	9.5
	14.0	8.0	-1.05	21.2
	20.0	12.0	-1.57	29.8
	26.0	16.0	-2.11	38.3
	38.0	22.0	-3.19	55.1
Sythas	8.0	6.0	-0.51	11.9
	16.0	8.0	-1.08	23.4
	20.0	12.0	-1.53	29.7
	26.0	16.0	-2.11	38.3
	38.0	20.0	-3.21	54.7

As expected, a strong correlation was observed between RDI_{12} and the percentage of streamflow reduction for each river basin. Since the reduction of streamflow is dimensionless and the climatic conditions are similar for all the river basins, a unique linear regression line (without intercept) could be used to link RDI_{12} and annual streamflow reduction ΔQ/Q (Eq. 1).

$$\frac{\Delta Q}{Q}\cdot 100 = -17.355\cdot RDI_{12} \qquad (RDI_{12}<0) \tag{1}$$

The linear correlation coefficient is 0.962 which indicates an excellent correlation.

Although this relationship is derived from the data of the above three rivers it applies successfully to several other basins of N. Peloponese. In any case, it should not be used for general use in other areas with different climatic and geomorphological data.

In practice, for the area under study, the use of the above regression equation means that for droughts in which -1>RDI>-1.50, the annual streamflow reduction is between 17.4 and 26%, whereas for more severe drought, -1.50>RDI>-2.00, the streamflow reduction may reach 34.7%. These figures can assist the water manager to take action in case he has early information on the oncoming drought. Therefore, the next step is to use the same logic and forecast drought conditions after 3 or 6 months from the beginning of the hydrological year.

3.2 Drought Severity Assessment for reference periods of 3, 6, 9 and 12 months

The proposed methodology was applied to the river basin of Mornos which is located in central Greece. This river basin is very important because it is the main provider of the potable water to the greater Athens area in which about 4 million people live. The proposed procedure was applied to the river basin corresponding to the site of an existing dam which was constructed in the late 70s.

The basic data for the basin under study are as follows:

- Area: 571 km^2
- Terrain: mountainous
- Mean altitude: 1020 m.a.s.l.
- Geology: flysh and limestone
- Meteorological stations: 8
- Duration of operation of stations: >40 years
- Period of analysis: 1962-2001
- Mean annual precipitation over the basin: 1140mm
- Mean annual potential evapotranspiration: 1238mm.

Based on the proposed methodology, meteorological data were transferred to the basin level and then RDI_3, RDI_6, RDI_9 and RDI_{12} were calculated for the period 1982-2001. These values are presented in Figure 3(a-d). For comparison purposes, the RDI values are presented together with SPI values for the same reference periods. As can be seen apart from slight deviations the two indices perform in a similar way. This can be interpreted as the possibility to use SPI in case RDI is difficult to calculate.

However, the most important conclusion from Figure 3 lies in the fact that there is a possibility to use these data for forecasting purposes. By comparing the results of drought indices of 3, 6, 9 and 12 months, it can be concluded that forecasts of the severity of drought for the entire year can be made quite early (e.g. after 3 or 6 months from the beginning of hydrological year). The possibility of using drought indices of the above reference periods for forecasting streamflow reduction is analysed elsewhere (Nalbantis and Tsakiris, 2008).

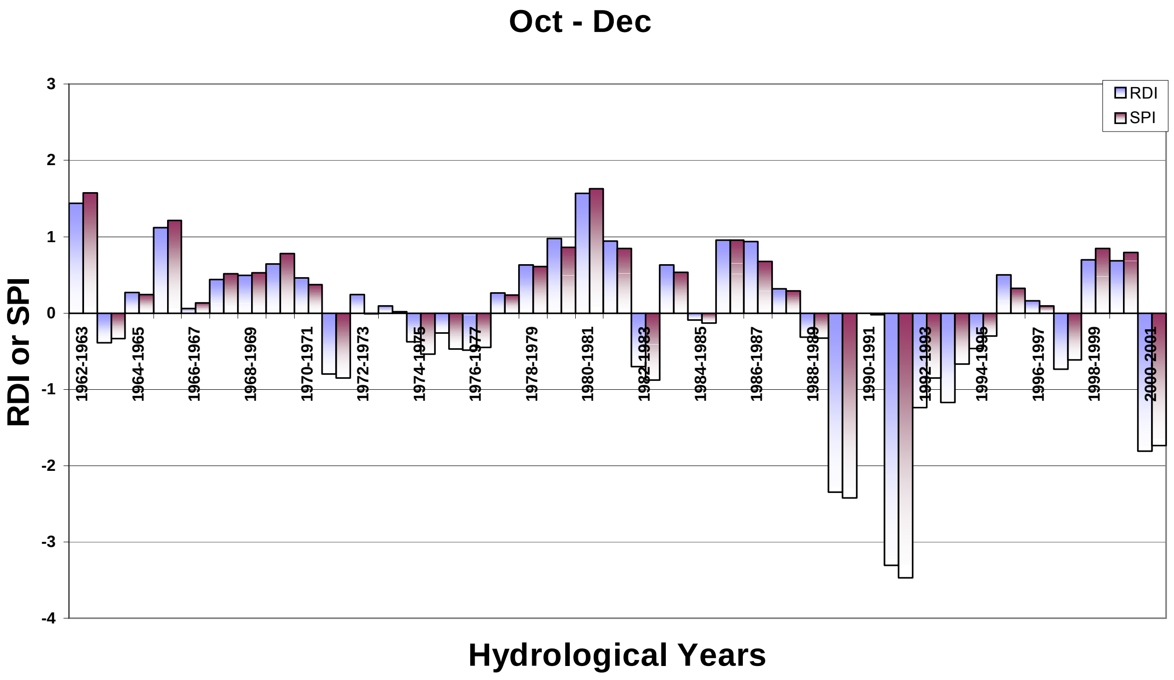

Fig. 3a. RDI and SPI for Mornos basin (1982-2001) for the reference periods Oct-Dec of each year.

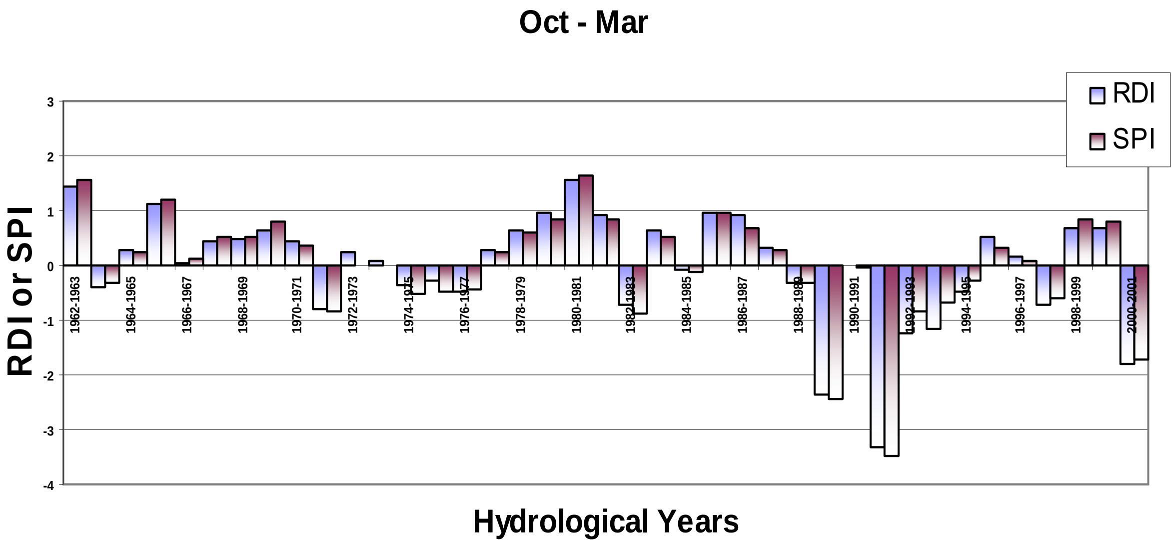

Fig. 3b. RDI and SPI for Mornos basin (1982-2001) for the reference periods Oct-Mar of each year.

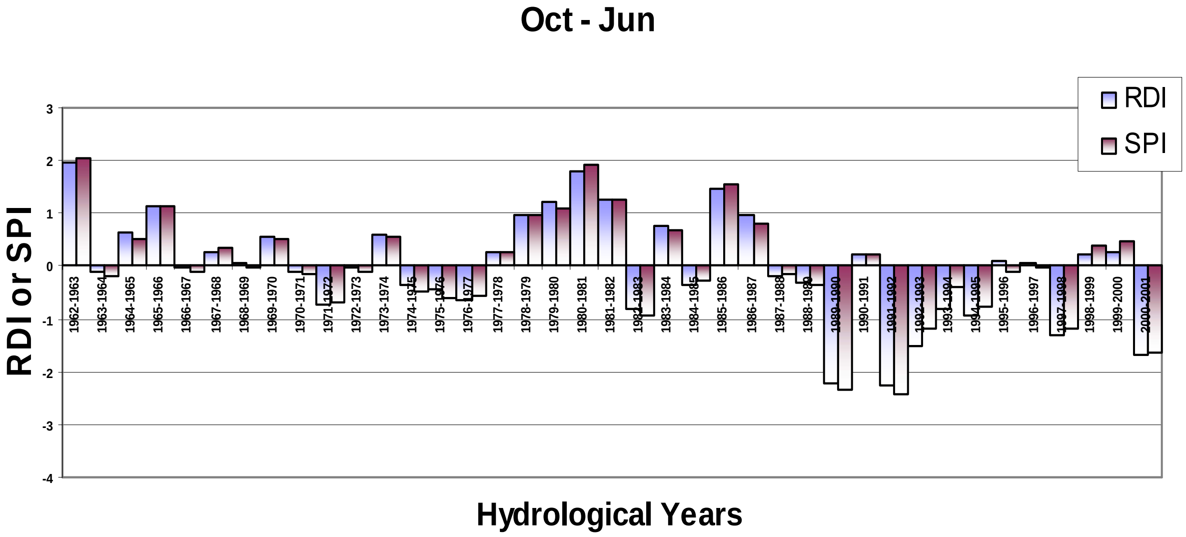

Fig. 3c. RDI and SPI for Mornos basin (1982-2001) for the reference periods Oct-Jun of each year.

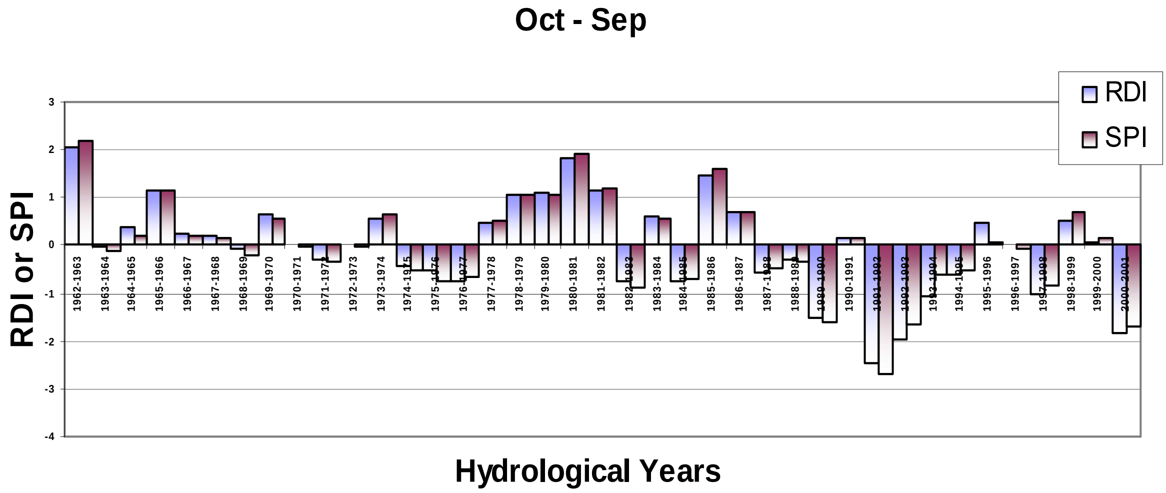

Fig. 3d. RDI and SPI for Mornos basin (1982-2001) for the reference periods Oct-Sep of each year.

4. DISCUSSION

The proposed simplified approach for the assessment of drought severity has obviously significant advantages in terms of the practical assessment and decision making against drought. Through two application studies it was shown that meaningful results on drought could be produced for entire river basins (spatial integration) and for predetermined reference periods (temporal integration). However, there are several assumptions which need further clarification since they induce constraints in the general application of the proposed methodology.

The fact that drought analysis is based on each year alone raises doubts on the correctness and fairness of the drought assessment since in most systems dry years have more significant consequences if they occur after a dry year than in the case they occur after a normal or a wet year. Also, a prolonged persistent drought lasting for several years could not be assessed through the proposed single year drought analysis. The multiyear drought effect could be modelled by considering an additive or multiplicative sequential consequences process. The multiyear drought consequences have been studied separately (Tsakiris et al., 2009).

Since drought is considered as the negative deviation from normal conditions of water availability, it is obvious that ‘normal’ conditions differ from place to place. The normal conditions are usually represented by the arithmetic mean or the median of a representative variable of water availability. For comparability purposes the truncation level below which drought occurs should be a figure preferably the same for each region. For stationary series a fixed value can be used whereas for periodic time series a set of seasonally varying truncation values seem more appropriate. Examples of this type of truncation levels have been used in the past. For example in the annual series of precipitation (P) and potential evapotranspiration (PET), the level of P/PET=0.20 could be used. This level is the boundary between sub-humid and semi-arid conditions.

An important final point for discussion is the replacement of RDI by SPI in case of not available data on variables which can be used for calculating potential evapotranspiration. As can be seen from the figures of the second application slight deviation between RDI and SPI can be observed. However the two indices behave in most of the studied cases in a similar manner. Statistically it can be proved through a large number of calculated values that RDI and SPI at least of the annual series are not usually significantly different. This means that annual PET is distributed with smaller coefficient of variation in comparison of annual P values. Therefore on the annual series the influence of PET is relatively small, provided that the series are stationary.

For shorter periods however the replacement of RDI by SPI should be made with caution since significant differences between the values of the above indices may be observed.

Last but not least is the question on the categorisation of drought and the boundaries between the various levels of drought. Two points are mentioned here. Firstly, it seems that the RDI and SPI boundary classes are not totally independent from the duration of drought, an assumption made in this paper. In other words there are concerns regarding the independency between the boundaries of drought categories of Table 1 and the duration of drought. Secondly, it seems more appropriate to use the concept of the ‘return period’ as indicator of the severity of drought than the standardised variables such as those used by RDI (or SPI). In any case, return periods are related directly to RDI (or SPI) and are more meaningful to engineers and scientists. Levels of return period 5, 10 or 20 years could be used as boundaries of moderate, severe and extreme droughts.

5. CONCLUDING REMARKS

A methodology is presented for replacing the three dimensional analysis of drought phenomena by a uni-dimensional analysis which can assist authorities and stakeholders to take rational decisions for combating droughts.

Simplifying assumptions were adopted and new temporal and territorial units were introduced such as the reference period and the river basin, respectively. A unique meteorological drought severity index was proposed, the Reconnaissance Drought Index, for the decision making process. The Standardised Precipitation Index could also be used in case of inability for calculating RDI.

Using the uni-dimensional approach, a more effective way for assessing the severity of drought is obtained. The proposed simplified method facilitates communication between water managers and stakeholders for reaching at rational decisions for facing drought.

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