European Water 9/10: 3-11, 2005.

Establishing a Drought Index Incorporating Evapotranspiration

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Abstract: A new general drought index is proposed for the assessment of meteorological drought severity. The new index called Reconnaissance Drought Index, RDI, is based on cumulative values of precipitation and potential evapotranspiration. Three expressions of RDI are given: the initial, the normalised and the standardised. The standardised RDI can be directly compared to the Standardised Precipitation Index (SPI) which is widely used. The new index has certain advantages when compared to SPI since it is more representative of the deficient water balance conditions than an index based only on precipitation.

Key words: meteorological drought, drought severity index, potential evapotranspiration, reconnaissance drought index.

1. INTRODUCTION

Drought is a recurring natural phenomenon associated with a deficit availability of water resources over a large geographical area and extending along a significant period of time (Rossi, 2000). This general definition adopted by engineers and scientists who are engaged in water resources management implies that drought is a regional phenomenon characterised by three dimensions: the severity or intensity, the duration and the areal extent (Rossi et al, 1992).

In a comprehensive analysis of a historical record for a certain region all the above dimensions could be separately or jointly analysed and modelled. However this task might be very complicated and therefore attempts are usually made for analysing each of these dimensions keeping the other dimensions constant.

The most important dimension of drought is its intensity. By the term “intensity of drought” we mean the significant reduction of water availability compared to some threshold corresponding to the so called “normal conditions”. Therefore establishing this threshold is the first step for calculating drought intensity. In most of the cases normal conditions are represented by the arithmetic mean or the median of water availability for a certain long historical record calculated for the same reference duration and the same geographical region. However this threshold may be replaced by a more representative figure related to “average” conditions dictated by the commonly performed activities in the region. Therefore the establishment of this threshold may be related to the activities in the area and not to the meteorological conditions alone.

The second step towards the calculation of drought intensity is to select the variables representing “water availability”. It is known that there are numerous definitions of drought most of which are of meteorological nature. However this paper adopts a water resources oriented definition.

In this context it is widely accepted that drought conditions in a region are caused by interactions between atmospheric processes and the variety of regional characteristics including the physical and the socioeconomic system. Recent studies proposed that the severity of drought should be assessed based on the anticipated damages it may cause to the various sectors of the economy, the environment and the society of the affected region (Tsakiris, 1994).

For simplicity the methodology presented in this paper is limited to the analysis of the natural processes only. Some of the most important parameters on which drought severity is depended upon are:

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

From these parameters the last is highly dependent on local conditions whereas the first and the second are related to climatic variability. In fact precipitation and potential evapotranspiration have been used for classifying bioclimatic aridity in a globally comparable way. In mathematical terms UNESCO (1979) used an aridity/humidity classification system based on average annual precipitation (P) divided by the average annual potential evapotranspiration (PET) (Table 1). According to UNESCO the potential evapotranspiration is calculated according to the Penman formula which requires data not easily found in most regions of the world. This led UNEP (1992) to propose a similar classification based on a more simplified approach for calculation of potential evapotranspiration proposed by Thornthwaite (1948) (Table 1) (Bruins, 1999). The index proposed by UNEP is used also by FAO and it is widely known as Aridity Index.

Table 1. Estimated and forecast global water withdrawal (km³/year)

Zone	**UNESCO (1979) P/PET (Penman method)**	**UNEP (1992) P/PET (Thornthwaite method)**
Hyper-arid	< 0.03	< 0.05
Arid	0.03 – 0.20	0.05 – 0.20
Semi-arid	0.20 – 0.50	0.20 – 0.50
Sub-humid	0.50 – 0.75	0.50 – 0.65
Humid	> 0.75	> 0.65

Regardless of the way potential evapotranspiration is calculated the classifications of Table 1 indicates that in order to reply to the question “how dry is dry” both precipitation and potential evapotranspiration are needed. Therefore the severity of dryness which is represented by these two parameters in the case of characterization of a region could be used for assessing the severity of a non-permanent phenomenon such as drought.

2. DROUGHT CHARACTERIZATION INDICES

Drought indices are important elements of drought monitoring and assessment since they simplify complex interrelationships between many climate and climate-related parameters. According to Wilhite et al (2000) indices make it easier to communicate information about climate anomalies to diverse user audiences allow scientists to assess quantitatively climate anomalies in terms of intensity, duration, frequency and spatial extent.

Since indices give important information useful for planning, designing and management applications of water resources related to various users and the environment, numerous indices have been proposed and used. Comprehensive reviews on these indices may be found in specific papers and publications (Richard and Heim, 2002, Hayes, 2004, Tsakiris et al, 2005, etc.).

Along the various indices proposed for characterization of meteorological drought two were widely accepted and used. Namely the Palmer’s Drought Severity Index (PDSI) (Palmer, 1965, Guttman et al, 1992) and the Standardised Precipitation Index (SPI) (McKee, 1995, Agnew, 2000, Tsakiris and Vangelis, 2004).

The Palmer Index was originally proposed for meteorological drought assessment. It uses precipitation, evapotranspiration and soil moisture conditions as the key determinants. The proposed procedure is based on the hydrological accounting and a number of assumptions which are either empirically chosen or location specific. PDSI is useful for drought assessment but not "sensitive enough" for being used in monitoring of drought.

On the opposite, the Standardised Precipitation Index (SPI) is using precipitation as the only determinant. The SPI is less complex than the Palmer Index and can be applied to any location using a transformation of precipitation data from a skewed distribution to the normal distribution. The main advantage of SPI is its simplicity whereas the main disadvantage is the use of only one meteorological parameter for describing the water deficit.

3. THE RATIONALE FOR USING POTENTIAL EVAPOTRANSPIRATION IN DROUGHT SEVERITY ASSESSMENT

From the presentation of drought characterization indices it may be concluded that SPI is more popular due to the least data requirements. The wide use of SPI during the last decades has already established its thresholds for drought characterization. However meteorological drought conceived as a water deficit should be approached by a sort of balance between input and output. The assumption that this deficit can be represented only through the estimation of input can not be valid in a wide spectrum of situations.

A step forward could be to consider the balance between two major meteorological parameters such as precipitation (P) (input) and potential evapotranspiration (PET) (output). Obviously the actual and not the potential evapotranspiration is the real output but the adoption of the actual evapotranspiration could complicate enormously the assessment of drought. Therefore PET can be selected as the key parameter representing the intensity of the atmosphere to extract water from the selected system. Analogously the input is not the recorded precipitation at a meteorological station but the portion of precipitation which is useful and effective for the system under study and not lost. If for instance a rainfed agricultural system is considered, the input from precipitation is the infiltrated precipitation or the so called effective precipitation.

Finally for simplicity reasons the recorded precipitation and the potential evapotranspiration (preferably calculated by Thornthwaite formula or evaporation from class A pan) are the parameters considered in the present analysis. The latter implies that only precipitation and temperature data are in essence required. These data could be easily found in monthly time step, practically everywhere.

Both precipitation and potential evapotranspiration are variables characterized by variability which differs from climatic area to climatic area, and it is heavily dependent on the time scale. Both variables are also characterized by seasonality in almost all climatic regions.

In arid and semi-arid regions the variability of precipitation is very high compared to PET which exhibits low variability mainly when a long time step is adopted.

In general both variables can be considered as "random" variables characterised by their arithmetic mean and their variance. However P and PET (monthly or annual) are not totally independent. In an attempt to express PET as a function of P, simple linear regression can be employed such as the one of Eq. 1.

$$PET = a + b \cdot P \qquad (1)$$

in which a and b are regression constants.

Although a variety of cases may be encountered, in the vast majority of them the regression parameter b is a negative number. Also in most of the cases the correlation coefficient is significantly less than zero.

To support the above findings the following two tables (Table 2 and Table 3) are presented from studies completed in the past at 11 stations covering Australia and therefore a variety of climatic conditions (Srikanthan and McMahon, 1983). In both tables evaporation data instead of PET have been used. As can be seen from Table 2 in all stations examined using annual values the correlation coefficient was negative and in 6 out of 11 stations it was significantly different from zero. Similar results are obtained for monthly data in the above 11 stations.

Table 2. Correlation coefficients, coefficients of determination, regression coefficients and standard errors of estimate for annual evaporation and precipitation (Eq. 1)

Station	No. of years	Correl. coeff.	Coeff. of Determin.	Regression a	Coefficient b	Standard error
Melbourne	11	-0.12	0.02	1450.7	-0.083	100
Sydney	9	-0.81*	0.66	2076.2	-0.230	73
Monto	12	-0.63*	0.42	1858.7	-0.333	76
Cowra	9	-0.93*	0.86	1891.8	-0.806	84
Brisbane	8	-0.27	0.07	1480.5	-0.047	48
Darwin	6	-0.69	0.48	3053.8	-0.149	75
Broome	12	-0.73*	0.54	3161.0	-0.463	146
Perth	12	-0.09	0.01	1886.4	-0.065	113
Adelaide	5	-0.83	0.69	1827.3	-0.416	37
Alice Springs	16	-0.83*	0.68	3695.7	-2.099	265
Kalgoorlie	14	-0.81*	0.65	3093.2	-1.609	137

*Significantly different from zero at 5% level.

Analogous results have been reported from a number of stations in Greece. A similar linear regression line is produced for an entire river basin in Central Greece, after transferring the data from all the 8 meteorological stations of the basin to the basin level according to their areas of influence (Fig. 1 and 2). It can be noticed that PET and P are negatively correlated. Therefore the water deficit between PET and P is higher if both variables are considered in the balance in comparison with the deficit based only on P.

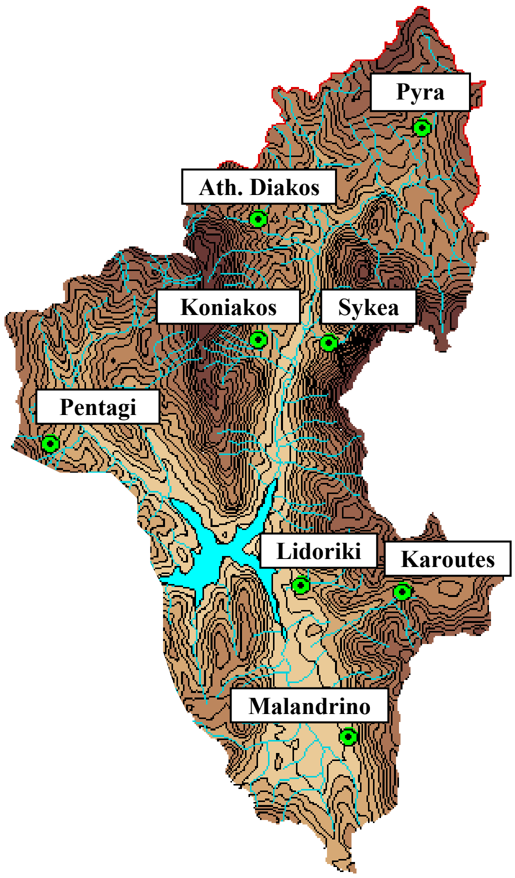

Figure1. Mornos river basin and its meteorological stations.

The conclusion of this analysis is that for the estimation of drought severity, apart from precipitation, the inclusion of evapotranspiration gives a more realistic estimate of water deficit. In other words if PET is omitted in this water balance (such as the case of drought indices like SPI) the severity of drought is underestimated. Also the effort to correlate a drought index with the anticipated damages is expected to be weaker in case of omitting PET.

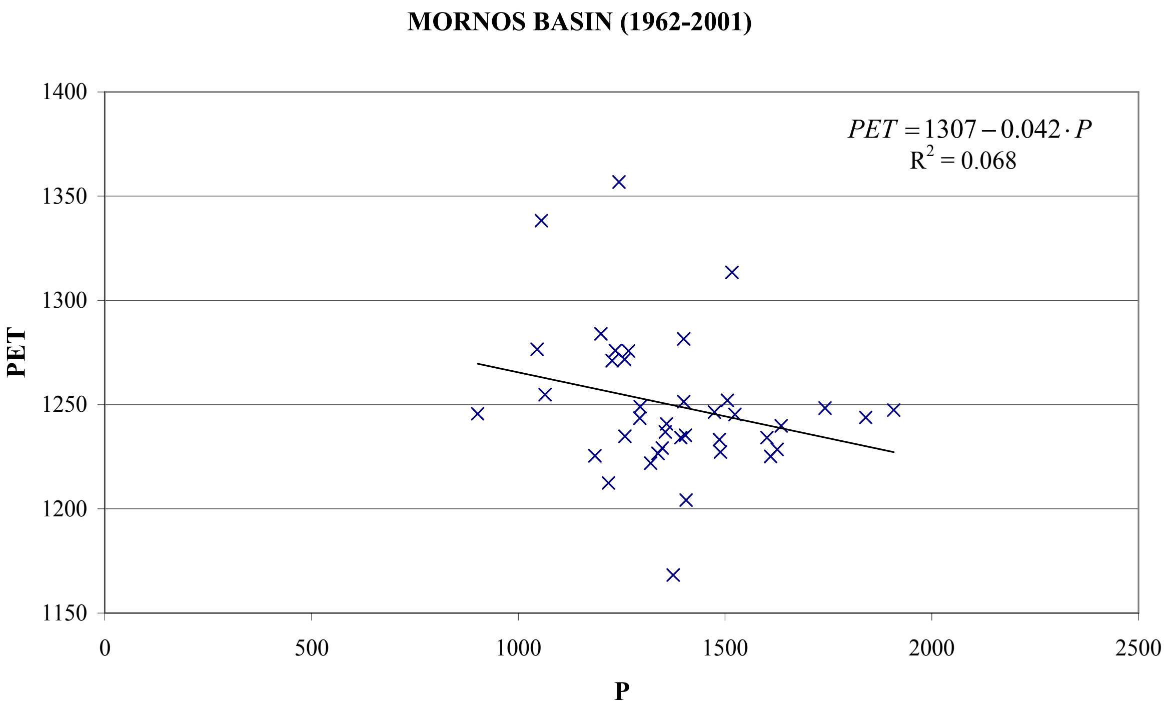

Figure 2. Annual PET against annual P for the entire river basin of Mornos in central Greece.

The use of PET in the analysis of water deficit is also supported by the fact that it is directly used in studies assessing the vulnerability of the water systems due to water shortage. It is worth mentioning that PET is the independent variable of both functions of Demand and Supply.

4. THE RECONNAISSANCE DROUGHT INDEX

A new drought characterization index is proposed in this paper. The new index called "Reconnaissance Drought Index – RDI" is based on the ratio between two aggregated quantities of precipitation and potential evapotranspiration. The initial value of the index for a certain period, indicated by a certain month (k) during a year, is calculated by the following equation:

$$a_k = \frac{\sum_{j=1}^{j=k} P_j}{\sum_{j=1}^{j=k} PET_j} \tag{2}$$

in which P_j and PET_j are the precipitation and potential evapotranspiration of the j-th month of the hydrological year. The hydrological year for the Mediterranean region starts in October, hence for October k=1.

Equation 2 may be calculated for any period of the year. It can be also written starting from any month of the year different than October if it is necessary.

For real world applications if a_k is calculated as a general indicator of meteorological drought it is advisable to use periods of 3, 6, 9 and 12 months. In case 12 month period is selected the result could be directly compared with the Aridity Index produced for the area under study. If a_{12} for a certain year is lower than Aridity Index calculated according to UNEP (1992) then the area is suffering from drought during this year.

Using monthly data of the hydrological year 1989-90 of precipitation and potential evapotranspiration of the meteorological station of Naxos island (Cyclades) (an area suffering from frequent droughts and water shortages) the graph of figure 3 was constructed. In this figure a_k is plotted for each month together with the average value, $\overline{a}_k$ and the threshold of $0.70 \cdot \overline{a}_k$ which is normally empirically considered as the value below which drought is severe. In this graph it can be noticed how drought develops during a dry year. Although October and November a_k is greater than $\overline{a}_k$ during the next months the situation is reversed, ending in a_{12}=0.079 compared with $\overline{a}_{12}$=0.203 (equal to the aridity index) and the $0.70 \cdot \overline{a}_{12}$=0.142.

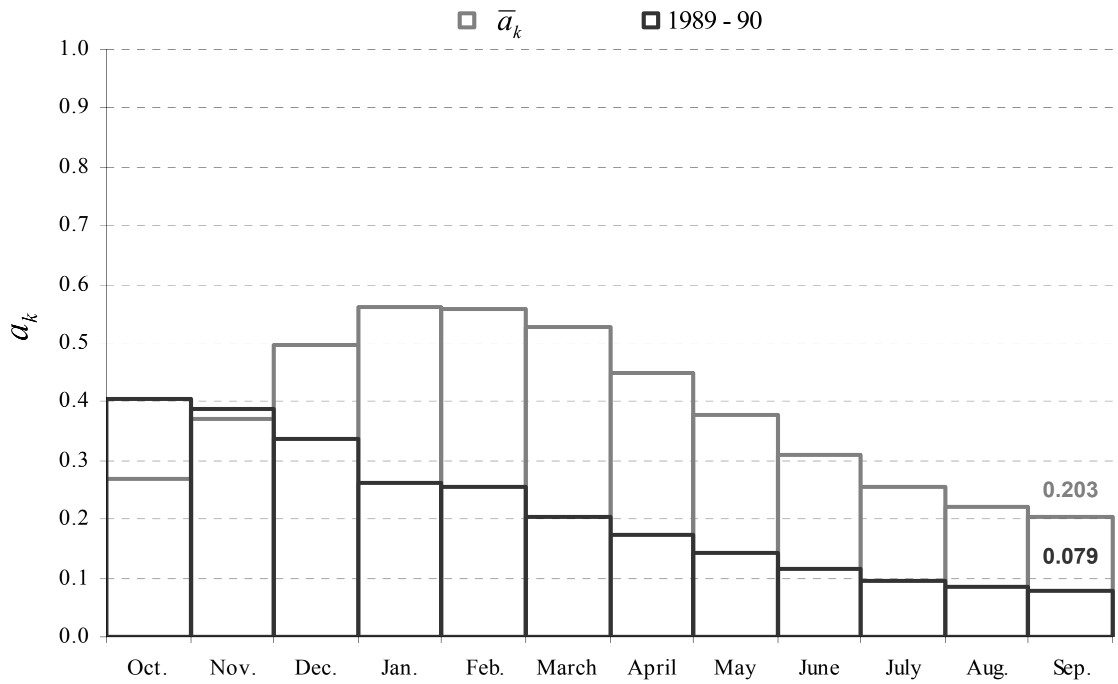

Figure 3. The development of a_k for the year 1989-90 for Naxos meteorological station compared to $\overline{a}_k$ and $0.70 \cdot \overline{a}_k$.

Calculating a_{12} for the period 1955/56 – 1991/92 and plotting it against each year it may be easily shown which years are considered dry since a_{12} of each year is directly compared with the aridity index $\overline{a}_{12}$ of the area. The deviation ($\overline{a}_{12} - a_{12}$) gives also a measure of the severity of drought of the year in question (Fig. 4).

The two expressions of the new index are the Normalised RDI and the Standardised RDI:

The Normalised RDI (RDI_n), is computed using the following equation

$$RDI_n(k) = \frac{a_k}{\overline{a}_k} - 1 \tag{3}$$

Finally the Standardised RDI (RDIst) is computed following a similar procedure to the one that is used for the calculation of SPI:

$$RDI_{st}(k) = \frac{y_k - \overline{y}_k}{\hat{\sigma}_k} \quad (4)$$

in which y_k is the $\ln a_k$, $\overline{y}_k$ is its arithmetic mean and $\hat{\sigma}_k$ is its standard deviation.

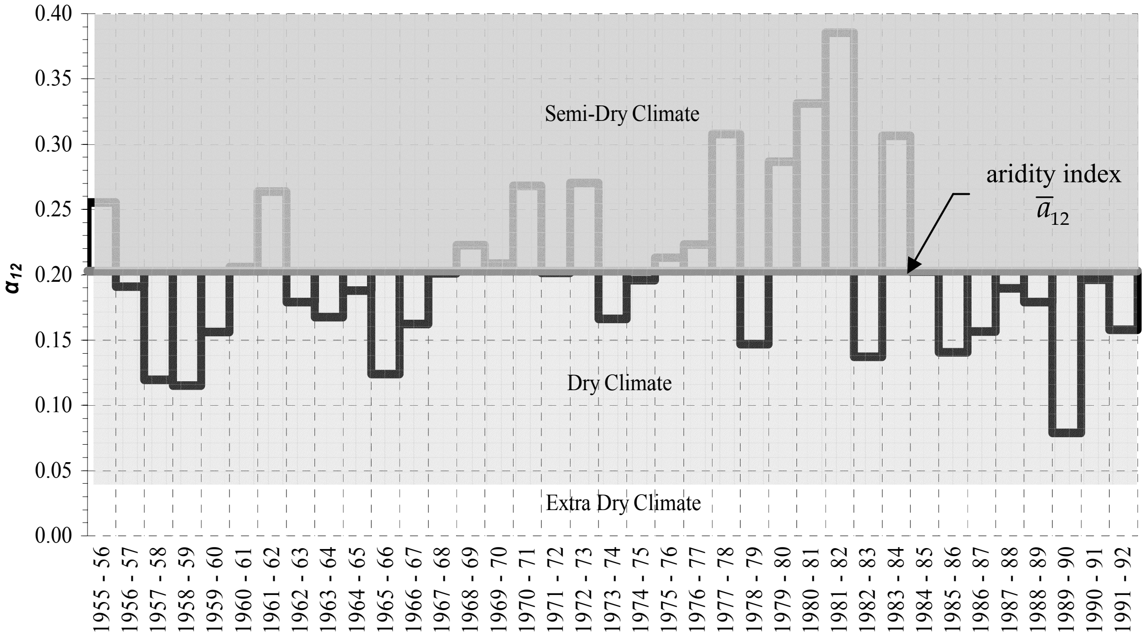

Figure 4. Annual a_{12} compared with the aridity index $\overline{a}_{12}$.

Figure 5 illustrates the yearly Normalised RDI [$RDI_n(12)$] for Naxos meteorological station for the period 1955/56 – 1991/92. The negative values show the dry years of the historical record. It can be seen that the most severe drought occurred during the year 1989/90. Interesting is also the fact that during the period 1985/86 up to 1991/92 all the years are considered dry since $RDI_n(12)$ is negative.

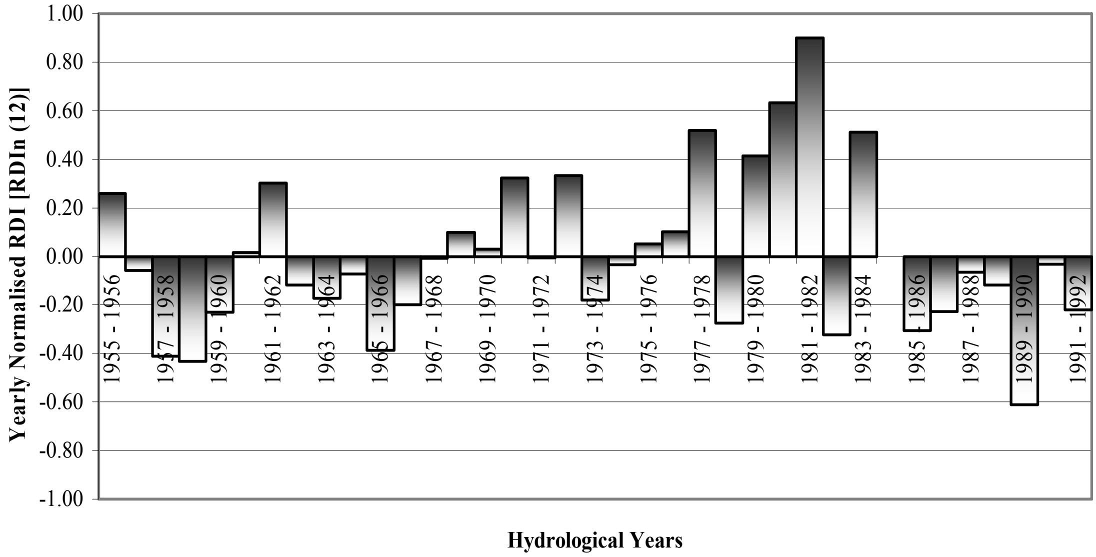

Figure 5. Normalised yearly RDI for Naxos meteorological station for the period 1955/56 – 1991/92.

Regarding Equation 4 the standardization is achieved by assuming that a_k follows a lognormal distribution. This assumption was tested using data from a variety of stations in Greece. Although the choice of lognormal distribution is not constraining (therefore other probability distributions could be used if appropriate) it does assist in devising a unique procedure for assessing drought severity.

The Standardised RDI (RDI_{st}), behaves in a generally similar way to the SPI and therefore the interpretation of the results is similar since the same thresholds as SPI can be used. Figure 6 illustrates the annual RDI_{st} for the same station (Naxos).

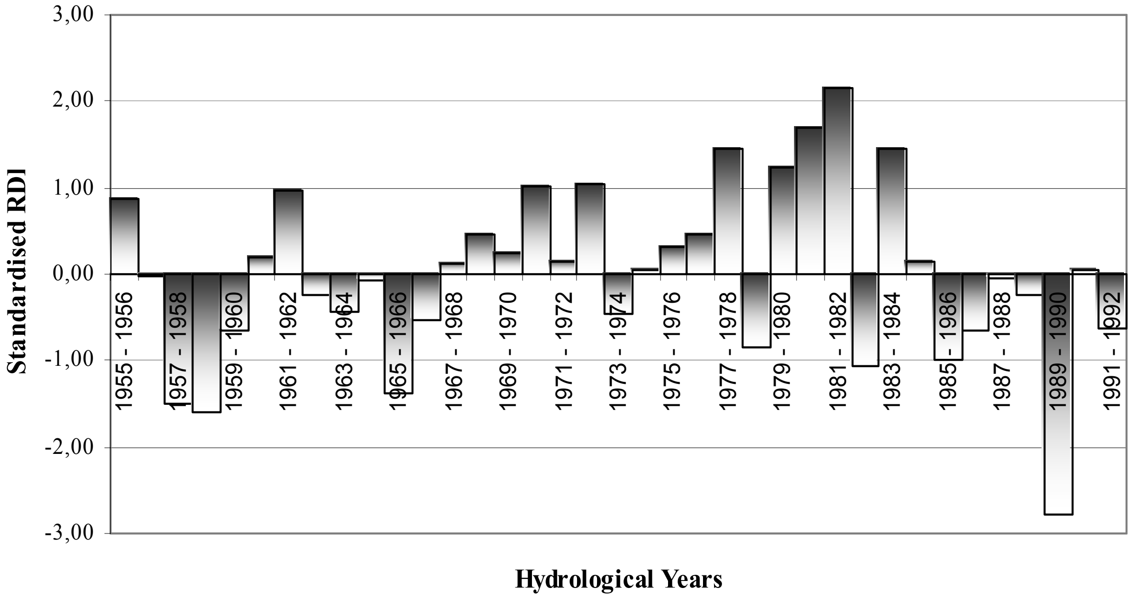

Figure 6. Annual RDIst for Naxos meteorological station

5. DISCUSSION AND CONCLUDING REMARKS

From the presentation of some popular indices for drought assessment it seems that SPI is becoming the most widely used index. This is probably due to its simplicity, universality and to its least data demanding nature. In this paper however it was shown that water deficit can not be estimated only on the input (e.g. precipitation) but also on the output variable (water consumption). Based on this logic a new index, the Reconnaissance Drought Index was proposed using data of two determinants, precipitation and potential evapotranspiration.

The new index is simple, universal and more comprehensive than SPI having a more sound scientific basis. Some of the advantages of RDI are summarised below:

1. It is physically based, since it calculates the aggregated deficit between the evaporative demand of the atmosphere and precipitation.
2. It can be calculated for any period of time. However 3, 6, 9 and 12 month periods are proposed since they are more useful for comparisons between different situations and locations. October, the first month of each hydrological year in the Mediterranean could be used as the initial month.
3. It can be more effectively associated with hydrological and agricultural drought.
4. The annual value of the initial index a_{12} may be directly compared with the Aridity Index of the area.
5. It is an ideal index to study the effects of climate instability conditions.

From the above it is concluded that RDI is a promising new index for the assessment of drought severity. Due to its easy calculation RDI can be used for monitoring purposes and to a certain extent for short period drought forecasting. In many cases of the Mediterranean basin in which there exists a well defined seasonal distribution of precipitation it seems very useful for water managers to know how the situation develops 3 or 6 months after October. This gives them the opportunity to adjust management plans for the late Spring and Summer during which demand is normally very high and no significant precipitation depths are expected to contribute towards the water balance of available quantities.

Further work on RDI is necessary mainly for the durations of 3 and 6 month periods so that collected data could be interpreted correctly. Also RDI should be related to demand functions in most of the water consuming sectors in order to build a more robust methodology for linking the index with the expected consequences which in turn will assist in determining the various severity thresholds of the index in a rational way. Associated with the latter is the study of the multiyear drought effects on the various systems affected by drought.

ACKNOWLEDGEMENTS

The paper is based on the research partially funded by the MEDAWater Programme of the European Commission within the framework of the Euro-Mediterranean Regional Programme for Local Water Management–MEDROPLAN project.

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