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Severity–duration–frequency analysis of droughts and wet periods in Greece

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Abstract There is an escalation in the frequency and severity of extreme events due to a number of environmental and/or anthropogenic factors. Droughts and exceptionally wet periods are regional phenomena, which are considered as major environmental extremes, especially in semiarid regions of the world, such as Greece. The development of severity–duration–frequency (SDF) relationships of droughts and wet periods over Greece is important in contemporary hydroclimatic and agroclimatic design and planning in the country. The Palmer Drought Severity Index (PDSI) is used for a quantitative description of droughts and wet periods. Statistical tests and visual inspection indicate that the EV1 (Gumbel) frequency distribution fits satisfactorily all the identified durations of droughts and wet periods, respectively. Moreover, the SDF curves show that decreasing frequencies (i.e. increasing recurrence intervals) correspond to increasing severities of droughts and wet periods, respectively. The developed SDF relationships are used to produce tables and isoseverity maps of Greece for each identified duration and all the selected return periods or frequencies, which constitute an essential aid for design purposes. The results of the study indicate that there is a decreasing pattern of the severities of droughts and wet periods from west to east and that, for similar durations and return periods, the wet spells are, in general, more extreme than droughts in Greece.

Analyse sévérité–durée–fréquence des périodes sèches et humides en Grèce

Résumé La fréquence et la sévérité des évènements extrêmes dus à différents facteurs naturels ou/et anthropiques augmentent. Les sécheresses et les périodes exceptionnellement arrosées sont des phénomènes régionaux, considérés comme des phénomènes extrêmes de première importance, en particulier dans les régions semi-arides comme la Grèce. L'établissement de relations sévérité–durée–fréquence (SDF) s'y révèle importante à l'heure actuelle pour la conception et la planification hydro et agroclimatique. L'indice de sévérité de sécheresse de Palmer (Palmer Drought Severity Index—PDSI) a été utilisé pour décrire quantitativement les périodes sèches et humides. Les tests statistiques et l'appréciation visuelle montrent que la distribution de Gumbel (Extreme Value 1—EV1) rend bien compte de l'ensemble des durées observées des périodes sèches et humides. Les courbes SDF montrent de plus que les évènements les plus sévères sont ceux dont la fréquence est la plus faible (c'est à dire ceux dont la durée de retour est la plus longue). Les relations SDF établies ont été utilisées pour élaborer à l'échelle de la Grèce des tables et des cartes d'égale sévérité pour différentes durées et pour différentes durées de retour qui constituent un outil essentiel d'aide à la conception. Les résultats de cette étude indiquent qu'il existe,

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pour une même durée et une même durée de retour, une tendance à la décroissance de la sévérité d'ouest en est, et que les épisodes humides sont, en général, plus sévères que les épisodes secs en Grèce.

INTRODUCTION

The climatic environment of uncertainty is one of the major threats in contemporary water resources management. There is an increasing trend towards a growth in water requirements in semiarid rural regions around the world, due mainly to several developmental agricultural activities (Dalezios & Bartzokas, 1993, 1995). Moreover, the rapid growth of the world population and the uneven distribution of resources have served to escalate both the frequency and severity of natural hazards and disasters, especially in semiarid regions (Dalezios, 1994). Furthermore, climate variability and change likely to cause the decrease of precipitation resulting in occurrence of drought periods, may negatively affect the water resources and harm agriculture in such regions. Specifically, the country of Greece belongs to a region in southeastern Europe in which the use of water resources is mandatory for agriculture (Dalezios *et al.*, 1991). Thus droughts as climatic extremes are more critical for agriculture than the average conditions.

Droughts and exceptionally wet periods are regional phenomena, which are considered as major environmental extremes. Although there is no universal definition of droughts, they are generally characterized by a prolonged and abnormal moisture deficiency (Palmer, 1965; Dalezios *et al.*, 1991). In agriculture, drought is described in terms of crop reduction and exists when soil moisture is depleted so that crop yield is reduced considerably (Prout *et al.*, 1986). In order to alleviate the impacts of droughts it is necessary to detect several drought features such as the onset of droughts, their areal extent, and severity (Dalezios *et al.*, 1991). There is an extensive literature for the quantitative assessment of droughts including indices, models and water balance simulation (Palmer 1965; Alley, 1985; Karl *et al.*, 1987; Prout *et al.*, 1986; Şen, 1998; Lana & Burgueno, 1998; Fernández & Vergara, 1998; Stahl & Demuth, 1999). In this study an "objective" index is used, namely the Palmer Drought Severity Index (PDSI), which addresses some of the described elusive drought properties (Palmer, 1965). This index can also be referred to as simply the Palmer Index, since it also evaluates wet periods.

There is a growing need for new planning and design of natural resources and environment based on the above mentioned scientific trends. For design purposes intensity–duration–frequency relationships have been used for a long time to synthesize the so-called "design storm" (Bell, 1969; Frederick *et al.*, 1977; Chen, 1983). Rural and agricultural development planning is related to updating and upgrading agroclimatic and hydroclimatic design by taking into consideration meteorological extremes, such as droughts and exceptionally wet periods. Agroclimatic and hydroclimatic designs refer to the analysis of climatic parameters, for example precipitation, temperature, evapotranspiration, etc., as well as agronomic parameters (cultivation species, natural vegetation, type of soils, etc.) and hydrological parameters (runoff, floods and droughts), respectively, in order to define homogeneous areas in this respect.

The purpose of this research study is to improve the understanding and analysis of droughts and wet periods in terms of their severity, duration, and frequency. The resulting relationships and models are essential in increasing the current state of knowledge in this field and in the planning of large-scale water resource systems. The objective of this paper is to develop quantitative relationships between drought parameters, namely severity, duration and frequency and use them in plotting drought isoseverity curves of certain return period and duration over Greece for improving agroclimatic and hydroclimatic design in the country. The computed PDSI time series from 28 stations with the same period of record (1957–1983) over Greece (Table 1) are used for the development of drought severity–duration–frequency (SDF) relationships, which are subsequently used for mapping drought isoseverity contours of certain duration and return period over Greece (Makris, 1995; Nitsiakos, 1995). The paper is organized as follows: in the next section, the computation of the PDSI is presented; in the third section the development of drought SDF relationships is described; and in the final section agroclimatic and hydroclimatic design and mapping is shown and discussed.

THE PALMER DROUGHT SEVERITY INDEX (PDSI)

The PDSI is referred to as an index of meteorological drought; however, the procedure considers precipitation, evapotranspiration, and soil moisture conditions, which are determinants of hydrological drought, i.e. the period during which the actual water supply is less than the minimum water supply necessary for normal functions in a particular region (Dalezios, 1994). In addition, the PDSI is standardized for different regions and time periods to facilitate direct comparisons of the PDSI between different regions (Guttman *et al.*, 1992).

The Palmer method used for calculating the PDSI has a number of limitations and deficiencies (Alley, 1984). The limitations of the method can be classified into two categories: the water balance model deficiencies and the PDSI characteristics. The first category of limitations of the Palmer method includes:

(a) The use of the Thornthwaite method (Thornthwaite & Mather, 1955) for the estimation of the potential evapotranspiration, although other methods could be employed. However, with the limited available data required by the Palmer method, only a simple methodology for the estimation of the potential evapotranspiration, such as the Thornthwaite method, should be used.

(b) The arbitrary amount of 25 mm of the moisture capacity of the surface soil layer. The soil moisture capacity could be widely changed depending on the climate, the soil texture, and vegetation coverage of the area.

(c) The assumption that the runoff is estimated without any lag in the time distribution. Thornthwaite & Mather (1955) and Mather (1981) suggested that 50–75% of the runoff should be delayed each month in order to reproduce monthly flow volumes observed in streams. The fraction of runoff delayed varies considerably depending on the depth and texture of the soil, the physiography and size of the basin, and the nature of the groundwater system.

(d) The "threshold-type" model of the Palmer method in that it assumes that runoff does not occur until the moisture capacity of the upper and lower soil layer is filled. This assumption tends to underestimate the recharge during the summer and early autumn months.

(e) No allowance is given for the effect of snowmelt or frozen ground but this is not a problem in the Mediterranean climatic region where snowfall occurs only at high elevations.

The limitations of the PDSI characteristics can be summarized as:

(f) the arbitrary definition of PDSI classes. These classes have been defined from data from central Iowa and Kansas;

(g) the sensitivity of PDSI values to *Kj* factors (equation (14) in this paper), while the overall duration of droughts of various magnitude are relatively insensitive to *Kj* variations; and

(h) the sensitivity of PDSI values to the climate of the calibration period.

Despite several assumptions made in the water balance calculations, its other limitations and deficiencies and the empirical nature of some of the standardized coefficients, the PDSI can be a useful tool for both research and operational drought assessment, if used appropriately and its limitations stated above acknowledged (Karl *et al.*, 1987; Rao & Voeller, 1997). It should also be mentioned that the Palmer method tackles the difficult problem of assessing droughts using only monthly data of precipitation and temperature.

The PDSI is already widely used mainly in the United States, where the index has been applied in countless research studies (for example, Karl, 1986; Kothavala, 1997; Piechota & Dracup, 1999), as well as on an operational basis (Lohani & Loganathan, 1997). Specifically, the National Weather Service provides information on the PDSI twice monthly for the severity assessment of droughts and wet spells across the United States. Similarly, in the "Weekly Weather and Crop Bulletin" the PDSI for climatic divisions of the United States is shown during the growing season (Alley, 1985). There are also successful applications of the PDSI in Canada (Louie, 1986) and other parts of the world as for example, Australia (Kothavala, 1999), Argentina (Scian & Donnari, 1997), and Hungary (Szinell *et al.*, 1998). The PDSI has also shown that it could be a useful tool for the detection of droughts in Greece (Dalezios *et al.*, 1991).

The data used in the computation of the PDSI in this study are monthly precipitation and temperature values from 28 synoptic meteorological stations in Greece (Table 1 and Fig. 1). The basic concepts and steps for computing the PDSI are presented here. The full procedure is described by Palmer (1965).

Step 1: hydrological accounting

The computation of the PDSI begins with a climatic water balance using long series of monthly precipitation and temperature records as inputs. The soil is divided into two layers, where the upper layer, called surface soil, contains 25 mm of available moisture at field capacity. This is the layer onto which the rain falls and from which evaporation takes place. Evaporation loss from the surface layer, L_S, is assumed to take place at the potential rate, which is estimated by the Thornthwaite method. Moisture cannot be removed from, or recharged to, the underlying layer until the surface layer has been depleted or saturated. The loss from the underlying layer, L_U, depends on the moisture content, computed PE, and available water capacity (AWC) of the soil system.
If $PE > P$, then:

$$L_S = \min\,[S_S, (PE - P)] \tag{1}$$

$$L_U = [(PE - P) - L_S]\, S_U / AWC \qquad L_U < S_U \tag{2}$$

where S_S and S_U are the amounts of available moisture stored at the beginning of the

Table 1 Meteorological stations used in the analysis (period 1957–1983).

No.	Station	Longitude	Latitude
1	Alexandroupolis (AL)	25°53′	40°51′
2	Anogia (AN)	24°53′	35°17′
3	Araxos (RX)	21°24′	38°10′
4	Volos (BL)	22°57′	39°22′
5	Corfu (KR)	19°54′	39°37′
6	Hellenico (EL)	23°43′	37°58′
7	Hiraklion (IR)	25°08′	35°20′
8	Ioannina (IO)	20°48′	39°42′
9	Komotini (KM)	20°24′	41°07′
10	Kos (KO)	27°18′	36°53′
11	Kavala (KV)	24°25′	40°56′
12	Kozani (KZ)	21°48′	40°18′
13	Lefkada (LF)	20°42′	38°50′
14	Lemnos (LM)	25°16″	39°53′
15	Larisa (LR)	22°25′	39°38′
16	Milos (ML)	24°26′	36°45′
17	Methoni (MU)	21°42′	36°49′
18	Mytilini (MY)	26°33′	39°06′
19	Nafplio (NA)	22°48′	37°34′
20	N. Filadelfia (NF)	23°00′	38°01′
21	Patra (PA)	21°44′	38°15′
22	Pyrgos (PY)	21°27′	37°40′
23	Soufli (SF)	26°18′	41°12′
24	Sitia (SH)	26°06′	35°12′
25	Tripolis (TP)	22°23′	37°31′
26	Trikala (TR)	21°46′	39°33′
27	Thessaloniki (TS)	22°58′	40°48′
28	Hania (SA)	24°02′	35°30′

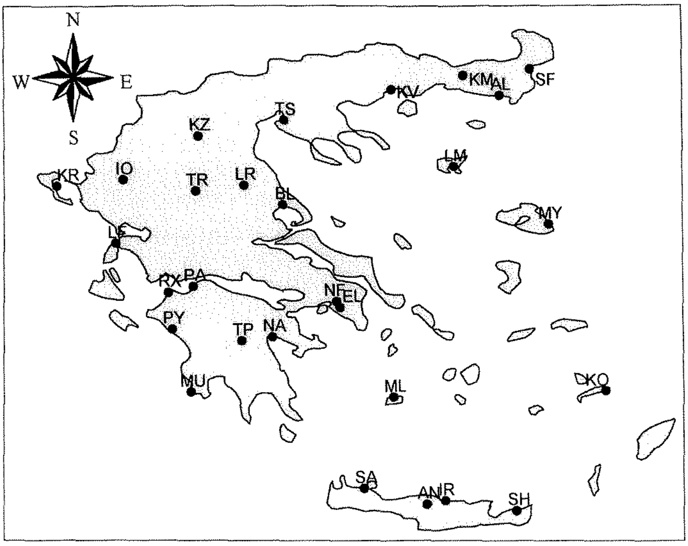

Fig. 1 Map of Greece with the stations used in the analysis.

month in the surface and the underlying layers, respectively. Runoff is assumed to occur, if and only if, both layers are at moisture capacity, AWC.

In addition to PE, three more potential terms are used and they are defined as follows: potential recharge (PR) is the amount of moisture required to bring the soil to its water holding capacity given by:

$$PR = AWC - (S_S + S_U) \tag{3}$$

Potential loss (PL) is the amount of moisture that could be lost from the soil by evapotranspiration during a zero precipitation period given by:

$$PL = PL_S + PL_U \tag{4}$$

where

$$PL_S = \min[PE, S_S] \tag{5}$$

$$PL_U = [PE - PL_S]S_U/AWC \qquad PL_U < S_U \tag{6}$$

The potential runoff (PRO) is defined as the difference between the potential precipitation and the potential recharge. Potential precipitation is equal to AWC, hence, PRO is given by:

$$PRO = AWC - PR = S_S + S_U \tag{7}$$

Step 2: climatic coefficients

A calibration of the water balance model for normal levels is accomplished by simulating the water balance over the period of available historical records of temperature and precipitation so that the moisture capacity of the lower soil layer and four coefficients for the study area are derived. The following four monthly coefficients are computed using the four potential terms, PE, PR, PRO and PL:

$$a_j = \frac{\overline{ET_j}}{\overline{PE_j}} \tag{8}$$

$$b_j = \frac{\overline{R_j}}{\overline{PR_j}} \tag{9}$$

$$c_j = \frac{\overline{RO_j}}{\overline{PRO_j}} \tag{10}$$

$$d_j = \frac{\overline{L_j}}{\overline{PL_j}} \tag{11}$$

where ET is the evapotranspiration, R is the soil water recharge, RO is the runoff, and L is the total water loss from the soil. The overbars indicate the average values from the historical records for each month j.

Step 3: CAFEC values

The derived coefficients are used to reanalyse the time series, in order to determine the amount of moisture required for "normal" weather during individual months. In particular, the Climatically Appropriate For Existing Conditions (CAFEC) values are computed, and they are denoted by a circumflex (^). For example, the CAFEC value for ET_J for month j is:

$$\hat{ET}_j = a_j \cdot PE_j \quad (12)$$

where PE_j is the potential evapotranspiration for the current month j. Hence, the CAFEC precipitation value, $\hat{P}$, is computed as:

$$\hat{P} = a_j \cdot PE + b_j \cdot PR + c_j \cdot PRO - d_j \cdot PL \quad (13)$$

Step 4: moisture anomaly index

For each month j, the difference between the actual precipitation and the CAFEC precipitation is an indicator of the water deficiency or surplus for that month at the station or area under study. This is expressed as $D = P - \hat{P}$. These departures (D) are converted into moisture anomaly (Z) indices, known as Z-index, according to:

$$Z = K_j \cdot D \quad (14)$$

where K_j is a weighting factor for the month j, which takes into account the spatial variability of departures D, such that they are independent of time and space.

Step 5: drought severity

In this final step the Z-index time series is analysed to develop criteria for the beginning and end of the periods of drought and a formula for determining drought severity. The following empirical expression for drought severity is used:

$$X_j = 0.897 \cdot X_{j-1} + \frac{Z_j}{3} \quad (15)$$

where Z_j represents the value of the moisture anomaly index or Z-index for the jth month and X_j is the value of PDSI for the jth month. The classification of weather based on PDSI (Palmer, 1965) is shown in Table 2. The same classification is adopted in this study based on Z-index.

DEVELOPMENT OF SDF RELATIONSHIPS FOR DROUGHTS AND WET PERIODS

The theory of extreme events in meteorology, hydrology and, generally, in natural sciences has been a research subject for the last few decades (Gumbel, 1958; Mehrotra

Table 2 Classification of weather using PDSI or *Z*-index (from Palmer, 1965).

PDSI or *Z*-index	Weather
> 4.00	Extremely wet
3.00 to 3.99	Very wet
2.00 to 2.99	Moderately wet
1.00 to 1.99	Slightly wet
0.50 to 0.99	Incipient wet spell
0.49 to -0.49	Near normal
–0.50 to –0.99	Incipient drought
–1.00 to –1.99	Mild drought
–2.00 to –0.99	Moderate drought
–3.00 to –3.99	Severe drought
< –4.00	Extreme drought

& Singh, 1998; Arnaud & Lavabre, 1999; Şen & Eljadid, 1999; Jenkinson, 1969). Statistical frequency analysis of climatic extremes, such as droughts, has been extensively used internationally with useful results for several hazards. However, droughts are not universally quantified phenomena and frequency analysis of droughts is not easily accomplished. Frequency of drought occurrence cannot sufficiently and fully cover the study of droughts, unless it is quantitatively related to other aspects and terms, such as severity and duration of droughts. This has led to the development of drought severity–duration–frequency (SDF) relationships.

In general, data for high-intensity extreme events are specified by three variables, namely: frequency, duration and either depth or mean intensity (i.e. severity). The areal extent of specific common drought episodes is another important feature of droughts, which is not considered in this study. The frequency of an extreme event is usually expressed by its return period or recurrence interval, which may be defined as the average interval of time within which the magnitude of the event is reached or exceeded once. The magnitude of an extreme event is given by the total depth occurring in a particular duration and data for extreme events can be usually presented by severity–duration–frequency graphs for several points throughout the region or the watershed of interest. For the estimation of extreme events, such as droughts, where knowledge of the return periods for events of particular depth and duration is required, it is necessary to assume a particular mathematical form of the frequency distribution. Several theoretical distributions have been tested against the cumulative severities (ΣZ values) of drought and wet periods of various durations. These include the Extreme Value 1 (EV1, Gumbel), the Generalized Extreme Value (GEV), the three parameter lognormal (LN3) and the log-Pearson (LP3) distributions (Stedinger *et al.*, 1993). Application of the non-parametric Kolmogorov-Smirnov two sample test at 95% confidence level and visual inspection of the fitting of the above theoretical frequency distributions to the ΣZ values indicate that the EV1 provides, overall, a reasonable and acceptable approximation of the frequency of the calculated ΣZ values (Fig. 2). Furthermore, the EV1 has been used in numerous extreme drought studies (for example, Gottschalk & Perzyna, 1993; Lana & Burgueno, 1998) and it is easier to apply since it is a two-parameter frequency distribution, contrary to LN3 and LP3. For the above reasons the EV1 has been used for the SDF analysis of droughts and wet periods in this study.

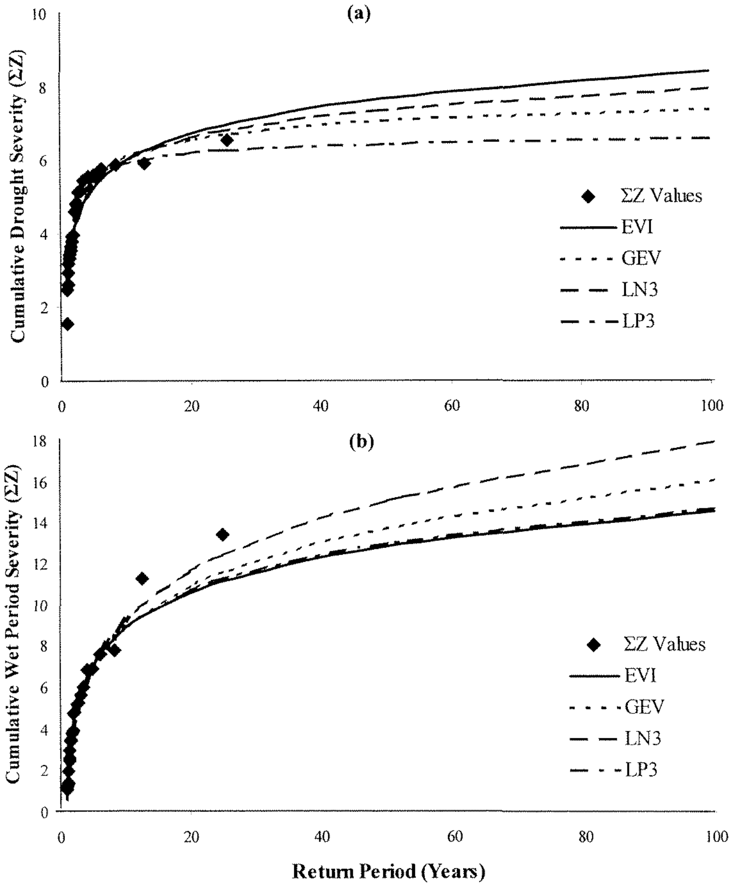

Fig. 2 Comparison of EV1 (Gumbel) and other theoretical frequency distributions for (a) cumulative drought (negative ΣZ values), and (b) cumulative wet period severities (positive ΣZ values) of three-month duration at Volos (BL) station.

The quantitative assessment of drought severity and duration appears to be a difficult subject. Since the objective of this study is agroclimatic and hydroclimatic design and planning, the severity of drought is defined as the cumulative sum of successive negative values of the *Z*-index (Σ*Z*) and the duration of drought is defined as the corresponding number of successive months with continuous negative *Z*-index values. Moreover, frequency of drought is defined as the return period of a specific cumulative *Z*-index (Σ*Z*) value for successive months. Similarly, the severity (or intensity) of wet periods is defined as the cumulative sum of successive positive values of the *Z*-index (Σ*Z*), and the duration as well as the frequency of wet periods are also defined as above.

The database for the development of the SDF relationships for droughts and wet periods consists of the computed monthly *Z*-index time series from 28 stations over Greece (Table 1). It should be mentioned that, for the development of the SDF relationships, a common period from 1957 to 1983 is used for the 28 stations. Two types of analysis were performed separately for each station, one for the drought periods, i.e. successive negative *Z*-index values and another for the wet periods, i.e. successive positive *Z*-index values. A brief description of the steps, which are followed to develop the drought SDF relationships, is presented.

Step 1: probability tables

Using the computed monthly *Z*-index time series, the drought episodes for each station are identified and tabulated based on the definition described above, i.e. the cumulative drought severity using successive (negative) values of *Z*-index (ΣZ) time series along with the corresponding duration in months. In this way multiple events per year are also accounted in the SDF analysis. As an example, Table 3 shows the recorded drought episodes of various durations for 10 stations. From this tabulated information for each station (Table 3), several tables are produced, one for each duration in months. A typical example is Table 4 for Volos (BL) station of three-month drought duration. The final number of produced tables is equivalent to the number of identified classes-durations for each of the 28 stations in Greece. An analogous procedure is followed for the cumulative positive *Z*-index values (ΣZ) in order to tabulate the wet periods with the corresponding duration for each station.

Table 3 Number of drought/wet episodes of different duration for 10 stations.

Duration (months)	Station: AL	AN	RX	BL	EL	IR	TS	IO	KV	KR
3	43/41	43/39	48/38	49/36	56/34	47/39	49/38	44/39	47/36	36/45
4	32/	32/32	36/	37/	41/	37/31	38/30	33/	37/31	29/37
4–5			/25		/21					
4–6	/24							/20		
4–7				/17						
5	26/	27/	30/	31/	32/	29/25	30/24	27/	30/26	/30
5–6		/24								19/
6	23/	23/	26/		28/	25/21	27/21	23/	24/22	
6–7				22/						/23
6–8			/17		/15					
7	20/21	20/	22/			22/18	23/18	21/	21/	
7–8		/18			22/				/17	
7–9										14/
7–12								/12		
8	/19		20/	21/		20/	20/		19/	/20
8–9	15/	15/		/15		/16	/15			
8–10								15/		
9			/16	18/	20/13		18/			
9–10			15/							
9–11						13/			14/	
9–12	/13	/13							/12	/13
10	13/	14/		/12	/12	/10	16/			12/
10–11			/13							
10–12				13/	15/		/12			
11			14/				13/			
11–12	10/	11/		/10	/10	/13		13/		9/
12			13/12			12/	13/		13/	

See Table 1 for explanation of station name abbreviations.

Step 2: fitting Gumbel distribution

For each drought duration and wet period duration the identified cumulative drought and wet period severities are plotted *vs* the corresponding return period and a statistical distribution is fitted to the plotted data points. Specifically, considering the example of Volos (BL) station, column 2 is plotted *vs* column 4, both in Table 4. The extreme value law (Farago & Katz, 1990; Demarée & Sneyers, 1986) is implemented to

Table 4 Probability table of cumulative drought severities (negative ΣZ values) of three-month duration for Volos (BL) station.

	Cumulative drought severity (ΣZ)	Exceedence probability	Return period (years)	EV1 (Gumbel)	95% upper confidence limit	95% lower confidence limit
1	6.54	0.04	26.00	6.97	8.47	5.47
2	5.91	0.08	13.00	6.24	7.45	5.03
3	5.85	0.12	8.67	5.80	6.85	4.76
4	5.75	0.15	6.50	5.49	6.41	4.56
5	5.57	0.19	5.20	5.23	6.07	4.40
6	5.55	0.23	4.33	5.02	5.78	4.26
7	5.45	0.27	3.71	4.84	5.53	4.14
8	5.15	0.31	3.25	4.68	5.32	4.03
9	5.12	0.35	2.89	4.53	5.12	3.93
10	4.82	0.38	2.60	4.39	4.95	3.83
11	4.8	0.42	2.36	4.26	4.78	3.74
12	4.61	0.46	2.17	4.14	4.63	3.65
13	3.94	0.50	2.00	4.03	4.49	3.56
14	3.91	0.54	1.86	3.91	4.36	3.47
15	3.77	0.58	1.73	3.80	4.23	3.38
16	3.65	0.62	1.63	3.70	4.11	3.28
17	3.53	0.65	1.53	3.59	4.00	3.18
18	3.44	0.69	1.44	3.48	3.89	3.08
19	3.33	0.73	1.37	3.37	3.78	2.96
20	3.17	0.77	1.30	3.26	3.67	2.84
21	2.94	0.81	1.24	3.14	3.56	2.71
22	2.61	0.85	1.18	3.01	3.45	2.56
23	2.6	0.88	1.13	2.86	3.33	2.38
24	2.48	0.92	1.08	2.68	3.20	2.17
25	1.55	0.96	1.04	2.44	3.02	1.85
		0.50	2	4.03	4.49	3.56
		0.20	5	5.19	6.00	4.37
		0.10	10	5.96	7.06	4.86
		0.05	20	6.70	8.09	5.31
		0.04	25	6.93	8.41	5.45
		0.02	50	7.65	9.42	5.88
		0.01	100	8.37	10.43	6.31

Notes:

The first column shows the ranking numbers; in the next column, the cumulative (negative) *Z*-index (Σ*Z*) values are given in ascending order. The corresponding probability (*P*) of occurrence (i.e. exceedence probability) is presented using the Weibull plotting position equation $P = m/(n + 1)$, where m is the current ranking number and n is the total number of data points, and the corresponding drought return period T of three-month duration is given using the equation $T = 1/P$, where P was previously defined. The last three columns show the Σ*Z* estimates of EV1 and the upper and lower 95% confidence limits, respectively.

drought severities by fitting the EV1 distribution (Gumbel, 1958), which has the following cumulative distribution function (cdf), F(x):

$$\mathrm{F}(x) = \exp[-\exp(-A \cdot (x - U))] \tag{16}$$

where A and U are the fitted parameters, which are computed for each duration from data and are equal to:

$$A = \frac{1.283}{\sigma} \tag{17}$$

$$U = \bar{x} + 0.45 \cdot \sigma \tag{18}$$

where $\bar{x}$ and σ are the mean and the standard deviation of the data, respectively.

The fitted EV1 distribution to the data points of Table 4 is shown in Fig. 2 for Volos (BL) station. The procedure of fitting EV1 distribution is applied to all the identified drought durations for each station. For illustrative purposes, Fig. 3 presents the plots of the fitted EV1 distribution to the different durations of droughts and wet periods for Volos (BL) station. As expected, each curve is plotted on top of the previous one, since it corresponds to ascending drought duration. Moreover, the data are occasionally grouped in high durations in order to enlarge the database and achieve an acceptable fit.

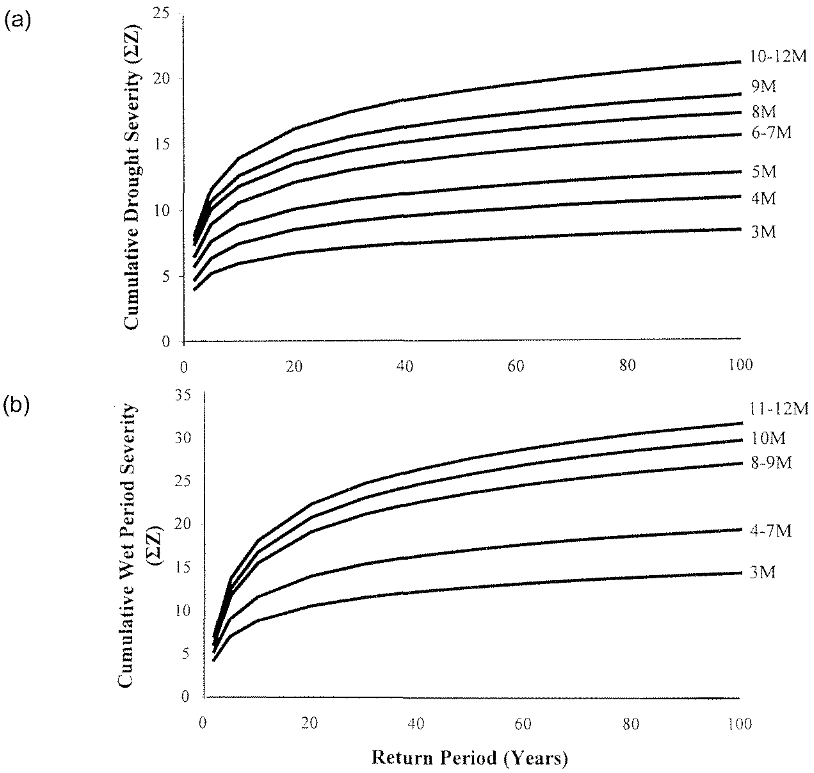

Fig. 3 Gumbel distribution plots for different durations (in months, M) at Volos (BL) station: (a) cumulative drought severities (negative ΣZ values), and (b) cumulative wet period severities (positive ΣZ values).

Step 3: severity–duration–frequency (SDF) curves

Using equation (16), drought and wet period severities (ΣZ) are computed, which correspond to return periods of 2, 5, 10, 20, 30, 50 and 100 years, respectively, for each identified drought duration. At this point, it should be mentioned that the low frequency events, i.e. events with return periods of 50 and 100 years have a much larger uncertainty than more frequent events. The reason for this implication is the small sample, which is what usually happens, and the extrapolation of the fitted theoretical frequency distribution to the most extreme events. However, the sample used in this study is reasonably long (27 years) thus the uncertainty of extreme events as is not high it shown by the 95% confidence limits indicated in Table 4 for the station of Volos (BL).

The SDF relationships are developed, using the ΣZ values with the above return periods, and the corresponding diagrams are produced for each station. For illustrative purposes, Fig. 4 shows the diagram of the drought and wet period SDF relationships developed for Volos (BL) station, where each curve refers to one of the above return periods. It should be mentioned that, since the SDF relationships are used for design purposes, whenever a grouping of durations occurs the curve is fitted to the highest duration within each grouping.

RESULTS OF SDF ANALYSIS FOR DROUGHTS AND WET PERIODS

The developed SDF relationships for droughts and wet periods, as previously described, are used for hydroclimatic and agroclimatic design and drought isoseverity mapping of Greece. This is accomplished by using the developed diagrams for each station, such as Fig. 4 for Volos (BL) station, to produce a table for each of the selected return periods of 2, 5, 10, 20, 30, 50 and 100 years. In particular, each table contains cumulative severities of droughts (negative ΣZ) and wet periods (positive ΣZ) for each identified duration and for the analysed 28 Greek stations. For illustrative purposes, Table 5 presents the cumulative severities of droughts and wet periods for identified duration and the return period of five years. Similarly, five more tables were produced for return periods of 2, 10, 20, 50, and 100 years (not shown here due to paper length limitations). In these tables each row consists of the severity (ΣZ) values for all the identified durations at each station, which correspond to each curve of the developed SDF diagrams, such as in Fig. 4. Each column of these tables constitutes the database for isoseverity mapping of Greece for specific duration and return period of either droughts or wet periods.

In the SDF analysis the Z-index is used, which characterizes the persistence of the drought phenomenon, whereas the PDSI accounts for drought severity (Alley, 1985; Karl, 1986). Since the analysis involves a combination of severities, durations and frequencies of droughts and wet periods, it seems that the Z-index can best delineate the SDF relationships.

The results presented in the series of tables, such as Table 5, are used to draw isoseverity maps using splines for the interpolation between the meteorological stations used in this study. It is evident from Table 5 that, for durations of up to seven months, there is a sufficient number of data points to draw isoseverity maps of either

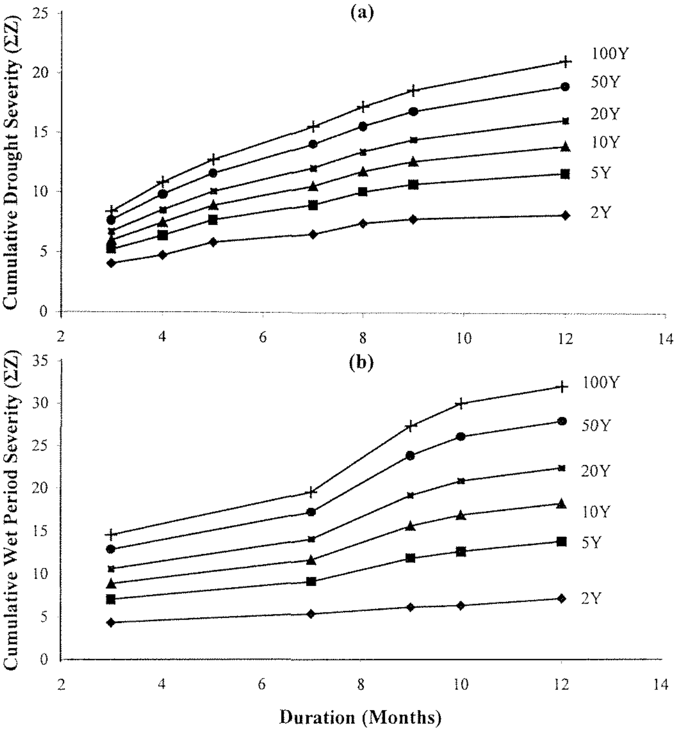

Fig. 4 Severity–duration–frequency curves of several return periods (in years, *Y*) for Volos (BL) station: drought severity (negative Σ*Z* values) and, (b) wet period severity (positive Σ*Z* values).

droughts or wet periods for Greece, which could be used satisfactorily for design and planning purposes. In fact, considering the above mentioned seven durations and the selected seven return periods, there could be at least 49 isoseverity maps of either droughts or wet periods for Greece. For illustrative purposes, Figs 5 and 6 show the isoseverity mapping of Greece for three-month duration and five-year return period of droughts and wet periods, respectively. Nevertheless, high durations are equally significant, since SDF relationships, and intensity–duration–frequency relationships in general, are developed for the design of extreme events. Moreover, grouping of high durations affects the high severity values (Σ*Z*). Thus, in the case of high durations, inferences on hydroclimatic and agroclimatic design and planning could be drawn from the series of tables, such as Table 5, and the series of SDF diagrams, such as in Fig. 4.

The results of this study, presented later, are discussed with respect to climate of Greece, which, in general, is a Mediterranean type climate with dry and hot summers (Mariolopoulos, 1938). However, there are five regions of Greece with distinct climatic characteristics, as follows:

(a) The western coast of Greece and the islands of the Ionian Sea, which receive large amounts of precipitation with maximum precipitation observed in autumn and minimum precipitation occurring during the summer months. The annual temperature range is relatively small in this region.

Table 5 Cumulative severities of droughts/wet periods for each identified duration and for return period of five years.

No.	Station	Duration of droughts/wet periods (months):									
		3	4	5	6	7	8	9	10	11	12
1	AL	5.1/8.2	6.5/	7.1/	7.5/9.9	8.2/11.6	/12.5	9.1/	10.4/		11.3/13.4
2	AN	4.7/8.5	5.9/9.6	6.5/	7.2/10.1	7.4/	/11.4	8.4/	8.7/		9.5/13.2
3	RX	6.1/8.8	7.3/	8.4/9.5	9.2/	10.1/	10.7/10.5	/11.9	12.4/	13.7/13.4	14.4/15.5
4	BL	5.2/7.0	6.4/	7.6/		8.9/9.1	10.1/	10.7/11.7	/12.6		11.8/13.7
5	KR	5.8/6.7	6.2/7.4	/8.4	7.2/	/9.5	/10.7	8.3/	8.7/		9.7/12.3
6	EL	5.7/7.6	7.0/	7.9/9.4	8.7/		9.9/10.7	10.8/12.0	/12.7		11.8/14.1
7	IR	5.8/9.9	6.8/11.7	7.3/13.3	7.8/14.4	8.6/15.8	9.3/	/17.1	/19.8	10.4/	11.9/22.2
8	IO	5.7/7.1	6.5/	7.2/	7.6/8.4	7.8/			8.9/		9.8/10.0
9	KO	5.5/10.3	6.6/11.8	7.3/	8.0/14.0	8.6/15.3	9.9/	10.4/16.2	/17.3	11.5/18.1	13.2/19.0
10	KM	5.6/9.4	6.8/	8.1/	9.2/	9.7/	10.7/11.1		11.6/	12.1/	12.5/13.3
11	KV	6.0/8.2	7.2/9.2	8.5/9.8	9.8/11.2	10.8/	11.6/13.2			12.6/	13.8/15.3
12	KZ	5.7/9.5	6.9/	7.7/	8.9/12.1	9.7/14.2	11.2/	13.1/	13.4/15.8	15.5/	17.7/17.0
13	LF	5.9/7.3	6.6/7.8	7.5/8.8	8.3/	9.1/9.6	/10.6		10.1/	11.4/	11.9/11.6
14	LM	5.6/8.8	6.9/9.7	7.9/10.8	8.7/13.1	9.5/14.2	10.0/17.5	/19.1		11.1/	12.0/20.7
15	LR	5.8/7.4	6.9/8.6	7.7/	8.1/	8.9/	9.5/	10.0/		11.3/	11.5/10.4
16	ML	6.2/7.9	7.3/9.0	8.1/9.8	8.8/11.5	/12.8		9.9/	10.5/14.4	/15.6	11.0/17.2
17	MU	6.2/9.0	7.4/10.0	8.6/12.6	9.9/13.1	10.4/14.6	11.3/	12.5/	13.8/	15.0/	16.3/15.5
18	MY	5.7/8.7	6.8/	7.6/9.8	8.7/11.0	9.4/	10.0/12.3	10.6/	11.5/	12.1/13.7	12.2/14.3
19	NA	6.1/9.1	7.4/10.3	9.0/11.6	10.1/13.0	10.8/14.3		11.5/15.2	12.3/		13.3/18.5
20	NF	5.7/7.1	7.0/8.8	7.8/	9.0/9.7	9.6/	/10.6	/12.1			10.5/13.1
21	PA	6.0/7.5	7.3/8.6	8.5/9.1	9.4/9.9	10.4/10.9	11.4/	12.7/12.1	13.7/12.8		14.2/14.7
22	PY	6.1/9.3	7.8/	9.0/11.7	9.9/14.4	10.8/15.4	11.9/17.5	13.0/18.4	14.4/19.5		15.6/21.4
23	SF	5.7/9.9	6.9/10.4	8.1/	9.1/11.9	/12.8	10.1/			11.3/	13.1/14.6
24	SH	5.6/7.8	6.8/9.5	7.3/11.4	8.0/12.5	8.9/	9.7/13.3		10.7/	11.2/	11.8/14.6
25	TP	5.7/7.1	6.7/	7.4/8.1	8.6/8.9	9.8/10.3	10.6/	12.1/	12.9/		14.5/11.3
26	TR	5.9/7.7	7.2/9.1	8.5/10.1	9.3/11.4	10.2/12.3	11.3/12.9	12.9/14.2	14.1/15.4	15.9/	16.6/15.8
27	TS	6.1/7.7	7.2/8.7	8.0/9.8	8.7/10.6	9.1/11.5	9.6/	10.8/12.1	11.9/	12.9/	13.9/13.2
28	SA	6.1/8.0	7.2/8.9	7.8/9.7	8.5/10.4	9.3/	10.2/		10.8/	11.4/	12.8/11.6

(b) The Aegean region, which includes the islands of the Aegean Sea, and the west coast of southern continental Greece. This region is characterized by low winter temperatures, high summer temperatures and low precipitation. The annual precipitation is, on average, half of that of the Ionian region.

(c) The continental region of northern and central Greece, characterized by long duration storms, short drought periods, low negative temperatures during winter, and large annual temperature range.

(d) The Mediterranean, desert-type region of Crete and southern Greece, with small annual precipitation and droughts of long duration.

(e) The mountainous region, which includes the Pindous Mountain range, which divides continental Greece into western and eastern regions, and the mountains of northern, central and southern Greece. The climate of this region is typical of mountainous areas with high annual precipitation and strong gradients of precipitation and temperature with elevation.

The series of tables, such as Table 5, and the corresponding isoseverity maps, such as Figs 5 and 6, show smooth and similar patterns for droughts and wet periods, respectively. Specifically, for droughts of five-year return period and three-month duration (Fig. 5) there is a smooth pattern over the continental part of Greece with mild to moderate severities. This pattern increases slightly towards south-southeast as well as northeast, as expected from the climatic classification of these regions presented above. As long as drought duration increases, the corresponding severity also increases, as expected, although at lower rates. At longer durations, such as 12 months, where the drought phenomenon tends to be rare, the pattern of isoseverity maps also remains smooth. Nevertheless, at durations from 6 to 12 months, there is also a weak decreasing gradient in drought isoseverity mapping from west to central Greece and then it slowly increases to eastern Greece. For all durations and return periods, there is a steep gradient and high values of ΣZ in the area of island of Crete, which is in agreement with the desert-type climate of this area as previously presented.

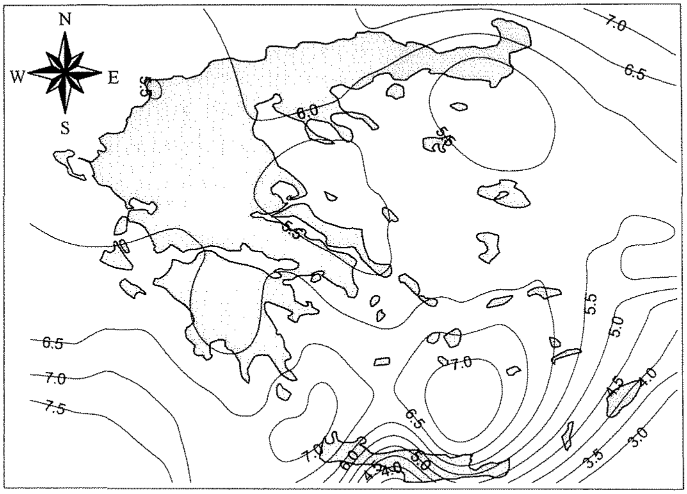

Fig. 5 Isoseverity (ΣZ) mapping of droughts in Greece for three-month duration and return period of five years (negative ΣZ values).

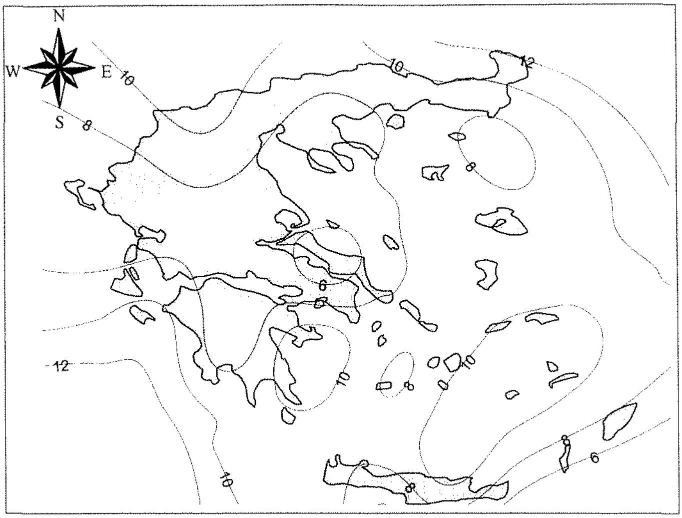

Fig. 6 Isoseverity (ΣZ) mapping of wet periods in Greece for three-month duration and return period of five years (positive ΣZ values).

Isoseverity mapping of wet periods follows similar patterns. In particular, in wet periods at five-year return period and three-month duration (Fig. 6), there is also a smooth pattern over the continental part of Greece showing very wet to extremely wet severities increasing towards southeast, north, and northeast.

At longer durations, there is a weak decreasing gradient in the severities of the wet periods from western to central and eastern Greece. Also, extremely wet severities are observed in the southeastern part of Greece with a strongly decreasing gradient north of the island of Crete.

The analysis indicates the need to further investigate droughts and wet periods over Greece, since there are differences between stations even in the same region, especially in droughts of long duration. Similarly, local extremes of wet periods, especially of long durations, should be further investigated.

In general, isoseverity mapping provides an additional potential in the study of extreme events especially for design purposes. The resulted patterns of isoseverity mapping have shown consistency with the climatic division in Greece, which has allowed regional comparisons of droughts and wet periods. The majority of droughts in Greece are characterized by short duration and mild severity, whereas wet periods appear less frequently with high severity (Dalezios *et al.*, 1991). Moreover, in all the stations in Greece, high frequency cycles of drought, i.e. drought periodicities from two to six months, dominate, whereas in individual cases low frequencies are also present (Dalezios, 1994). These findings are reflected in the developed SDF relationships and the produced tables, as well as in isoseverity mapping.

SUMMARY AND CONCLUSIONS

Severity–duration–frequency (SDF) relationships of droughts and wet periods were developed leading to isoseverity mapping of Greece which could be used for hydroclimatic and agroclimatic design and planning. The Kolmogorov-Smirnov two-sample test and visual inspection of the fitting indicated that the EV1 distribution satisfactorily fitted all the identified durations of droughts and wet periods. Moreover, the final SDF curves appeared to be as expected, since for decreasing frequencies (i.e. increasing recurrence intervals) there is a corresponding increase in severities of droughts and wet periods, respectively, which tend to become asymptotic to the x-axis (Fig. 4).

Isoseverity mapping of Greece, as could be inferred from Table 5 and Figs 5 and 6 (which were presented for illustrative purposes), indicated that there are drought periods of common duration over the various regions of Greece. Moreover, isoseverity mapping of Greece also shows smooth and similar patterns for droughts and wet periods, respectively. These patterns appear to indicate increasing severities towards the northeast as well as south-southeast. Droughts have lower severities than wet periods for similar durations and return periods according to the Palmer severity classes (Table 2), indicating that, in general, wet spells have higher intensity than droughts.

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