Spatio-temporal drought analysis in the Trakya region, Turkey

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Abstract Since droughts are natural phenomena, their occurrence cannot be predicted with certainty and thus it must be treated as a random variable. Once drought duration and magnitude have been found objectively, it is possible to plan for the transport of water in known quantities to drought-stricken areas either from alternative water resources or from water stored during wet periods. The summation of deficits over a particular period is referred to as the drought magnitude. Drought intensity is the ratio of drought magnitude to its duration. These drought properties at different truncation levels provide significant hydrological and hydrometeorological design quantities. In this study, the run analysis and *z*-score are used for determining drought properties of given hydrological series. In addition, kriging is used as a spatial drought analysis for mapping. This study is applied to precipitation records for İstanbul, Edirne, Tekirdağ and Kırklareli in the Trakya region, Turkey and then the drought period, magnitude and standardized precipitation index (SPI) values are presented to depict the relationships between drought duration and magnitude.

Key words spatio-temporal drought; duration; deficit; intensity; magnitude; run analysis; SPI

Analyse spatio-temporelle des sécheresses dans la région de Trakya, en Turquie

Résumé Dans la mesure où les sécheresses sont des phénomènes naturels, leur occurrence ne peut pas être prévue avec certitude et doit donc être considérée comme une variable aléatoire. Une fois que la durée et l'amplitude de la sécheresse ont été évaluées objectivement, il est possible de planifier le transport d'eau, pour des quantités connues, vers les zones victimes de sécheresse depuis des ressources en eau alternatives ou depuis des stocks mobilisés en périodes humides. L'intensité de la sécheresse est le rapport entre l'amplitude de la sécheresse et sa durée. Ces propriétés de la sécheresse, avec différents niveaux critiques, fournissent des grandeurs hydrologiques et hydro-météorologiques significatives pour la planification. Dans cette étude, nous utilisons l'analyse de séquences et le score centré réduit pour déterminer les propriétés des sécheresses de séries hydrologiques données. De plus, nous utilisons le krigeage pour analyser les sécheresses dans l'espace et produire des cartes. Cette étude est une application à des enregistrements de précipitation à Istanbul, Edirne, Tekirdağ et Kırklareli dans la région de Trakya, en Turquie. Nous présentons les périodes de sécheresse et les valeurs d'amplitude et d'indice standardisé de précipitation (ISP) afin de décrire les relations qui existent entre la durée et l'amplitude de la sécheresse.

Mots clefs sécheresse spatio-temporelle; durée; déficit; intensité; amplitude; analyse de séquence; ISP

INTRODUCTION

Droughts are extreme hydrological events that may adversely affect the social, economic, cultural, political and other functions of a region. Drought predictions may prevent these adverse consequences to a significant extent. In order to reach such a target, it is necessary to develop a method of prediction based on the available past experiences as well as on environmental conditions. Drought occurrences are rather complex, since they depend on various interactions of many hydrological phenomena such as precipitation, runoff, evaporation, infiltration, and surface and groundwater storages.

There are several indices that measure to what extent precipitation for a given period has deviated from historically established norms. Although none of the major indices is inherently superior to the rest in all circumstances, some indices are better suited than others for certain uses. For example, the Palmer (1965) drought severity index (PDSI) has been widely used in Turkey as a means of providing a single measure of meteorological drought severity, for example for the previous 30 years. It is based on a monthly water balance accounting scheme involving precipitation, evapotranspiration, runoff and soil moisture. The PDSI has been used in making operational water management decisions and planning drought monitoring.

Basic drought phenomena and drought preparedness studies are presented by Wilhite & Glantz (1985) and Wilhite (1996). In order to understand whether a deficit of precipitation has different impacts on the groundwater, reservoir storage, soil moisture, snowpack, and streamflow, McKee *et al*. (1993) developed the standardized precipitation index (SPI). The SPI was designed to quantify the precipitation deficit for multiple time scales, which reflect the impact of drought on the availability of different water resources. Soil moisture conditions respond to precipitation anomalies on a relatively short time scale, while groundwater, streamflow, and reservoir storage reflect the longer-term precipitation anomalies. For these reasons, McKee *et al*. (1993) originally calculated the SPI for 3-, 6-, 12-, 24-, and 48-month moving average time scales. The SPI is probability-based and was designed to be a spatially invariant indicator of drought which recognizes the importance of time scales in the analysis of water availability and water use. It is essentially a standardizing transform of the probability of the observed precipitation (Guttman, 1999). It can be calculated for a precipitation total observed over any duration desired by a user. It is well known in practice that short-term durations (weeks or months) are important to agricultural activities, whereas long-term durations (seasons, years, etc.) are significant in water supply management.

McKee *et al*. (1993) used the classification system that is normalized so that wetter and drier climates can be represented in the same way by means of the SPI. In addition, wet periods can also be monitored using the SPI (McKee *et al*., 1995). They also defined the criteria for a "drought event" for any of the time scales. A deficit occurs any time that the SPI is negative. The accumulated magnitude of deficits during a dry period is referred to as drought magnitude, and is the sum of the absolute values of SPI for all the months within a drought event.

DROUGHT FEATURES

Conceptual definition of drought implies statistical chance combinations of persistently recurrent precipitation events. Precipitation deficit, which is also referred to as a dry spell, can be expressed in terms of dry period in basic time units of hours, days, weeks, months or years. Most often, in drought assessments, monthly dry and wet spells play significant roles in water management. However, for long-range drought estimations, annual basic periods are taken into consideration. It is well known, from the behaviour of precipitation phenomena, that short basic time scales include strong non-stationary dynamics. Most of the drought prediction formulations are based on the probability, statistics and stochastic approaches where the stationarity is taken as a fundamental assumption. Yet, the validity of the stationarity assumption for natural phenomena over long time intervals is very problematic.

Similar considerations can be made about the regional behaviour of droughts, but in this case, homogeneity or heterogeneity of the areal extent come into play. If each sub-area of the drought-affected region has the same chance of being dry or wet, then such a drought occurs according to homogeneous regional features, otherwise heterogeneity must be considered in the modelling. From a climatic viewpoint, agricultural droughts have quasi-cyclical components and such quasi-periodicity is usually difficult to preserve in models, lacks suitable explanations and has rather low predictive utility. In order to achieve successful predictability, it is necessary to have records of the basic data on precipitation, evapotranspiration, temperature, etc.

In the mathematical modelling of droughts, most often precipitation records are taken as the basis, where a time series of records, X_1, X_2, X_3, ..., X_n, is truncated at a threshold precipitation value, X_0, as shown in Fig. 1. Hence, simply and conceptually, the drought is defined on the basis of comparing a given precipitation time series with a threshold value and, according to their relative positions, different drought features appear. Among these features, the following objective properties can be identified and they are all random, probabilistic or statistical in their behaviour.

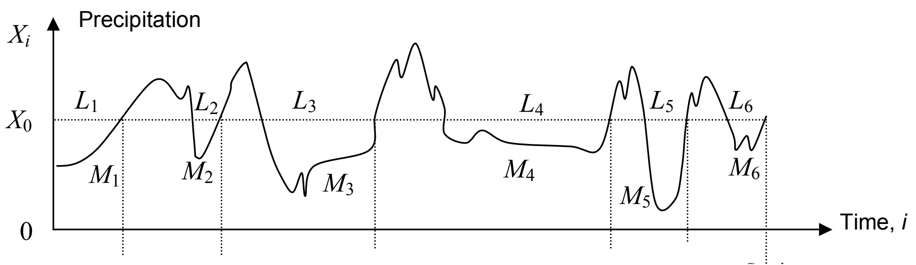

Fig. 1 Schematic representation of wet and dry spells. (M_i: drought magnitude; L_i: drought duration).

A wet spell occurs when any time series value at the *i*th instant is greater than the threshold level, ($X_i > X_0$). Accordingly, the difference ($X_i - X_0$) > 0 is named as the precipitation surplus. Otherwise, a dry spell takes place as ($X_i < X_0$). Accordingly, the difference ($X_0 - X_i$) < 0 is the precipitation deficit. A sequence of wet spells preceded and succeeded by a dry spell is referred to as the duration of wet period during which there is no water supply problem. If the two successive dry spells that separate a wet period are X_i and X_j, then the duration of this wet period is equal to $(j - i + 1)$. Similarly, if a sequence of dry spells is preceded and succeeded by a wet spell, it is referred to as the duration of dry period. If the two successive wet spells that separate a dry period are X_k and X_l, then the duration of this dry period is equal to $(l - k + 1)$. Additionally, if a dry spell (precipitation deficit) is followed by a wet spell, then there is a transition from the drought period to the wet period (precipitation surplus).

Similarly, if a wet spell is followed by a dry spell, there is a transition from the wet period to the drought period.

The summation of water deficits during the whole drought period gives the total drought severity. This is equivalent to the accumulated precipitation excess needed to offset the drought. Finally, the division of this accumulated precipitation deficit by drought duration gives the average drought severity.

In the context of uncertainty techniques, it is possible to calculate almost all objective drought quantities statistically or probabilistically, provided that observation records are available. Among the statistical values are average, standard deviation, correlation coefficient and skewness values, in addition to grouped data evaluation in terms of histograms (referred to as relative frequency diagrams with the theoretical counterpart being the probability distribution function, pdf). On the other hand, if the interest lies in the frequency of drought occurrence, then the probability statements can also be calculated from the same record. For instance, $P(X_i > X_0)$ and $P(X_i < X_0)$ express simply the basic probabilities of precipitation surplus and deficit, respectively. These basic probabilities help to construct a probabilistic model that may be used in predicting agricultural drought duration (Şen, 1989, 1990).

There is no procedure to date for predicting accurately the time occurrence of drought duration or areal drought extension. Various subjective approaches employed for drought estimation in the past ended in surprising failures. In modern times, drought estimations are sought on the basis of objective and systematic scientific procedures and, along this line, probability theory and statistics provide a convenient framework for drought occurrence predictions. In general, these techniques are used for depicting the quantitative relationships between various drought characteristics. For instance, the multiple regression analysis or Monte Carlo simulation techniques are used to evaluate regional and temporal drought frequencies.

The majority of drought analyses have concentrated on temporal assessments. The first classical approach to statistical analysis of droughts has involved the evaluation of an instantaneously smallest value in a measured sequence of a basic variable recorded at a single site (Gumbel, 1963). This method gives information on the maximum value of drought duration magnitude within a prescribed period of time such as 10, 25, 50 or 100 years. Yevjevich (1967) presented the first objective definition of temporal droughts. Its applications have been performed by Millan & Yevjevich (1971), Şen (1976, 1977, 1980a,b), and Sırdaş (2002). Due to the analytical difficulties, studies of regional droughts have been carried out to a relatively lesser extent. In fact, the first study along this line was carried out by Tase (1976), who performed many computer simulations to explore various drought properties. Different analytical solutions of drought occurrences have been proposed by Şen (1980b) through the random field concept. However, most of these studies are limited in the sense that they investigate regional drought patterns without temporal considerations. Spatial variability and frequency analysis of droughts are presented by Horn (1989) and Lee *et al*. (1986).

The main purpose of this study is to identify various drought properties on the basis of run analysis and *z*-score with applications to four stations in the north-western part of Turkey. Empirical relationships are provided through scatter diagrams between the drought magnitude and length.

z-SCORE AND RUN ANALYSIS

Sometimes, *z*-scores are referred to as "standard scores". The *z*-score transformation is especially useful when seeking to compare the relative standings of items from distributions with different means and/or different standard deviations. Further, *z*-scores are especially informative when the distribution to which they refer, is normal. In every normal distribution, the distance between the mean and a given *z*-score cuts off a fixed proportion of the total area under the curve. Statisticians have provided tables indicating the value of these proportions for each possible *z*-score.

The *z*-score values are similar to the standard precipitation index (SPI), which is a special application of the transformation rules. The SPI for an item indicates how far and in what direction that item deviates from its distribution's mean, expressed in units of its distribution's standard deviation. The mathematics of the SPI transformation are such that, if every item in a distribution is converted to its *z*-score, the transformed scores will necessarily have a mean of zero and a standard deviation of one.

The *z*-score for precipitation is simply the standardization of a given time series, X_i as $X_1, X_2, ..., X_n$. The standardized precipitation series, x_i is:

$$x_i = \frac{X_i - \overline{X}}{S_x} \tag{1}$$

where $\overline{X}$ is the arithmetic mean and S_x is the standard deviation of the series. The application of the same concept for different moving average orders is in fact referred to as the standardized precipitation index. However, without moving averages, the *z*-score and the standardization are equivalent to each other. The *z*-score and SPI are defined theoretically as the sub-areas under a normal (Gaussian) probability distribution function. The SPI has many advantages over other drought indices, such as the Palmer approach, which requires more variables. The SPI approach needs consideration only of two parameters, the arithmetic mean and standard deviation. Furthermore, in the statistical literature the procedure in equation (1) is referred to as the standardization procedure. It is equivalent to *z*-scores in the meteorological literature (Wu *et al*., 2001).

Here, only empirical calculations of drought descriptions, such as mild (MID), moderate (MOD), severe (SED) and extreme (EXD) drought cases are carried out, and, accordingly, the classifications are done crisply at a single site; the SPI categories are shown in Table 1 (McKee *et al*., 1993, 1995). As a sample description, various drought characteristics are shown in Fig. 1.

Empirically, drought descriptions are investigated by moving averages of 3, 6, 12, 24 and 48 months. First, temporal drought characters are determined using the run analysis. Drought magnitude, M_j, is defined as:

Table 1 Standardized precipitation index categories.

SPI Values	Category	Abbreviation
0 to –0.99	Mild drought	MID
–1.00 to –1.49	Moderate drought	MOD
1.50 to –1.99	Severe drought	SED
< –2.00	Extreme drought	EXD

$$M_j = \sum_{i=1}^{m} \left| X_0 - x_i \right| \tag{2}$$

where m is the number of deficits during a drought period and X_0 is the standardized truncation level for each drought description, as 0, –1.0, –1.5 and –2.0. The standardized truncation level is calculated from equation (1) as:

$$\left(X_0 - \overline{X}\right) / S_X$$

and is selected from the SPI classification (Table 1). Finally, the drought intensity I_j of the jth dry period is defined as the ratio of drought magnitude to drought duration, L_j, as:

$$I_j = \frac{M_j}{L_j} \tag{3}$$

Spatial treatment of droughts is mostly achieved by either probabilistic modelling or spatial analysis such as kriging, multiple regression or trend surface analysis. Although there are also spatio-temporal drought analysis methodologies, they are rather restrictive and have many assumptions in order to simplify the analysis. So far, there is not a single definition of drought or drought index that has been suitable for all interests and purposes. Perhaps, the main reason for a lack in such a common definition arises from the fact that there are several kinds of information needed for drought monitoring. Hence, in addition to precipitation, runoff, soil moisture, relative humidity, evaporation, temperature, etc., variables are also necessary as basic information. Most of the studies to date, have concentrated on precipitation shortages as signs of drought, because precipitation is the most significant input variable for many water-related processes such as water supply, groundwater and reservoir storage, soil moisture, snowpack and streamflow. The simplest methodology of temporal drought assessment is the combination of run analysis and standardized precipitation index (SPI), which are used herein to quantify the precipitation deficit for several time scales, i.e. time averaging periods.

APPLICATION

The Trakya region lies in the northwestern part of Turkey (Fig. 2) and is characterized by a modified Mediterranean type of climate with influences from the Black Sea maritime and Balkan continental effects. Consequently, winters are cold and summer seasons are rather warm with long sunshine duration and high relative humidity.

Application of the *z*-score and run analysis methodology is presented for the cities of İstanbul, Edirne, Tekirdağ, and Kırklareli in the Trakya region (see Fig. 2). Over 60 years of precipitation data are available, between 1931 and 1991, and Fig. 3 shows time series of monthly, 2-monthly and 3-monthly moving average of standard precipitation for each city. It is clear that all monthly *z*-score time series have more values above the zero level, which is due to the fact that Turkish monthly precipitation amounts are log-normally (or Gamma) distributed and, therefore, high and low values are not symmetrical. However, 2-monthly and 3-monthly moving averages appear in a more balanced manner between the high and low precipitation values (Fig. 3).

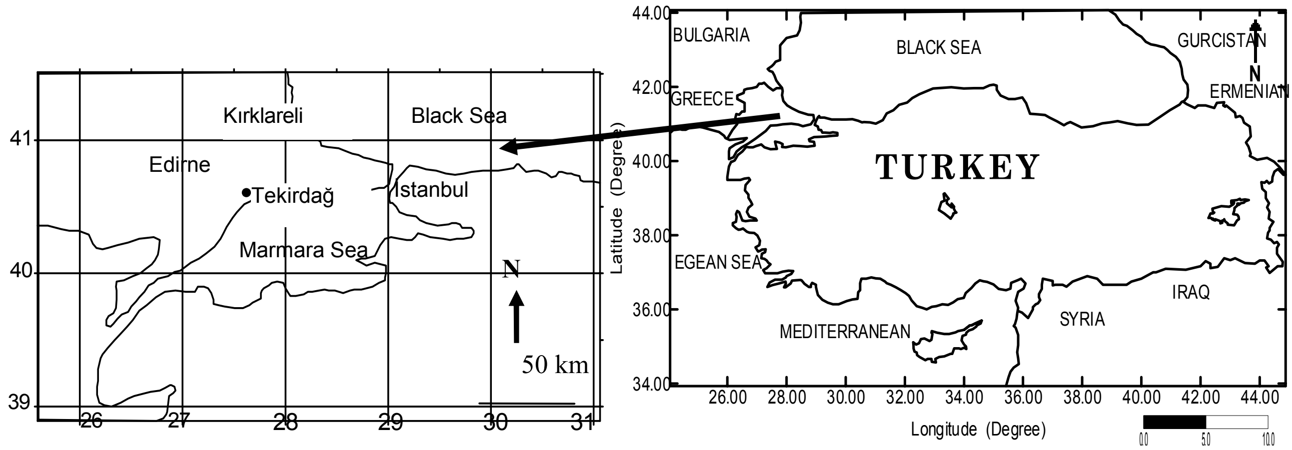

Fig. 2 Location map of the Trakya region, Turkey.

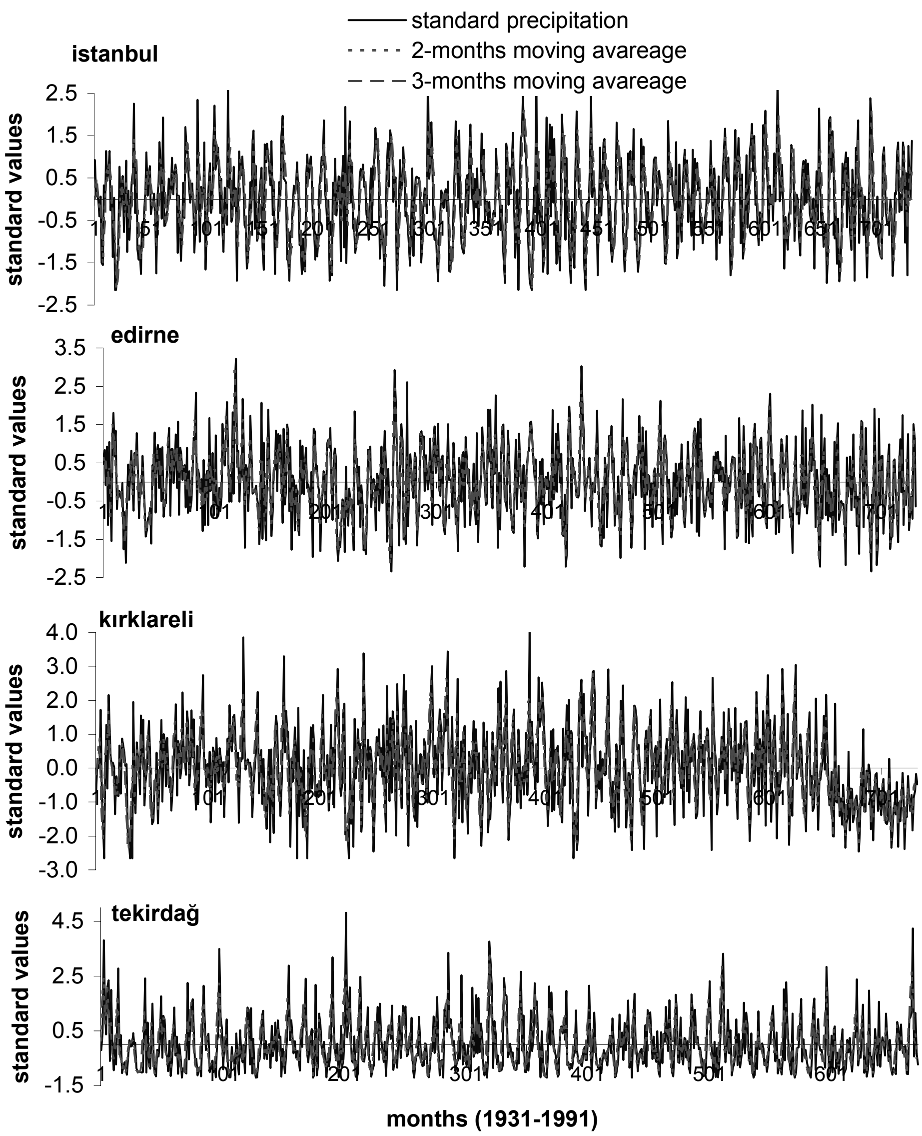

Fig. 3 Monthly, 2-monthly and 3-monthly standard precipitation time series for the Trakya region, Turkey.

Table 2 Statistical parameters of duration, magnitude and intensity for different truncation levels.

Parameters	Istanbul			Edirne			Kirklareli			Tekirdağ		
	M	*L*	*I*	*M*	*L*	*I*	*M*	*L*	*I*	*M*	*L*	*I*
Truncation level 0:												
Max	0.83	12	0.28	1.17	12	0.29	1.08	3	0.36	1.17	12	0.29
Min	0	1	0	0	1	0	0	1	0	0	1	0
Median	0.12	1	0.11	0.14	1	0.13	0.14	1	0.14	0.14	1	0.13
Average	0.18	1.49	0.12	0.2	1.55	0.13	0.21	1.32	0.14	0.2	1.55	0.13
St. deviation	0.18	1.42	0.08	0.21	1.53	0.08	0.22	0.57	0.09	0.21	1.53	0.08
Skewness	1.6	5.84	0.38	2.3	5.56	0.14	1.98	1.65	0.34	2.3	5.56	0.14
Truncation level –1:												
Max	5.47	13	0.74	5.54	12	0.7	2.74	5	0.61	4.53	12	0.67
Min	0	1	0	0	1	0	0.01	1	0.01	0.01	1	0.01
Median	0.49	2	0.34	0.44	1	0.35	0.58	2	0.33	0.48	2	0.32
Average	0.92	2.31	0.34	0.77	2.1	0.32	0.73	2.05	0.3	0.85	2.25	0.33
St. deviation	1.04	1.99	0.18	0.89	1.81	0.17	0.65	1.14	0.16	0.9	1.82	0.17
Skewness	1.96	2.48	–0.01	2.5	2.67	–0.13	1.24	1	–0.21	1.79	2.68	–0.03
Truncation level –1.5:												
Max	8.34	15	1.06	9.13	13	0.93	6.18	9	0.88	6.59	12	1.05
Min	0	1	0	0	1	0	0.02	1	0.02	0.01	1	0.01
Median	0.71	2	0.42	0.72	2	0.46	0.93	2	0.42	0.87	2	0.47
Average	1.22	2.48	0.43	1.25	2.46	0.45	1.24	2.49	0.43	1.55	2.9	0.44
St. deviation	1.37	2.17	0.22	1.5	2.23	0.21	1.21	1.61	0.21	1.56	2.28	0.23
Skewness	2.24	2.68	0.07	2.92	2.51	–0.12	1.88	1.48	–0.05	1.08	1.51	0.01
Truncation level –2:												
Max	8.34	15	1.07	8.97	13	1.08	6.18	9	1.02	6.59	12	1.05
Min	0	1	0	0	1	0	0.02	1	0.02	0.01	1	0.01
Median	0.76	2	0.44	0.75	2	0.46	0.94	2	0.43	0.87	2	0.47
Average	1.32	2.55	0.45	1.31	2.49	0.46	1.37	2.57	0.45	1.55	2.9	0.44
St. deviation	1.42	2.18	0.23	1.53	2.23	0.22	1.33	1.65	0.24	1.56	2.28	0.23
Skewness	1.99	2.57	0.09	2.54	2.38	–0.01	1.59	1.34	0.26	1.08	1.51	0.01

Table 2 shows various statistical parameters concerning drought duration, magnitude and intensity based on run analysis values at standard truncation levels of 0.0, –1.0, –1.5 and –2.0, respectively. These drought features refer to past observations, but their statistical parameters are useful for what-if analysis, conditionally valid also for the future. For instance, one can find drought magnitude, which corresponds to a given drought duration, as shown in Fig. 4(a)–(d). For instance, given the expected drought duration of 13 months for Edirne, it is possible to read drought magnitude from Fig. 4(a) as approximately 8.97. The real magnitude, M_r (in mm) can be calculated for any given station from the reverse relationship in equation (1) as:

$$M_r = MS_M + \overline{X}_M \tag{4}$$

where S_M and $\overline{X}_M$ represent standard deviation and the arithmetic average value, respectively. This corresponds to the average water need in a critical period that should be met using "external" water resources, i.e. accumulated in other time periods or spatial locations (e.g. water stored in a reservoir during a wet period, or water transfer from another, wetter catchment). The total water need in the critical period for Erdine is approximately 273.08 mm. It is clear from Fig. 4(a)–(d) that increases in the drought

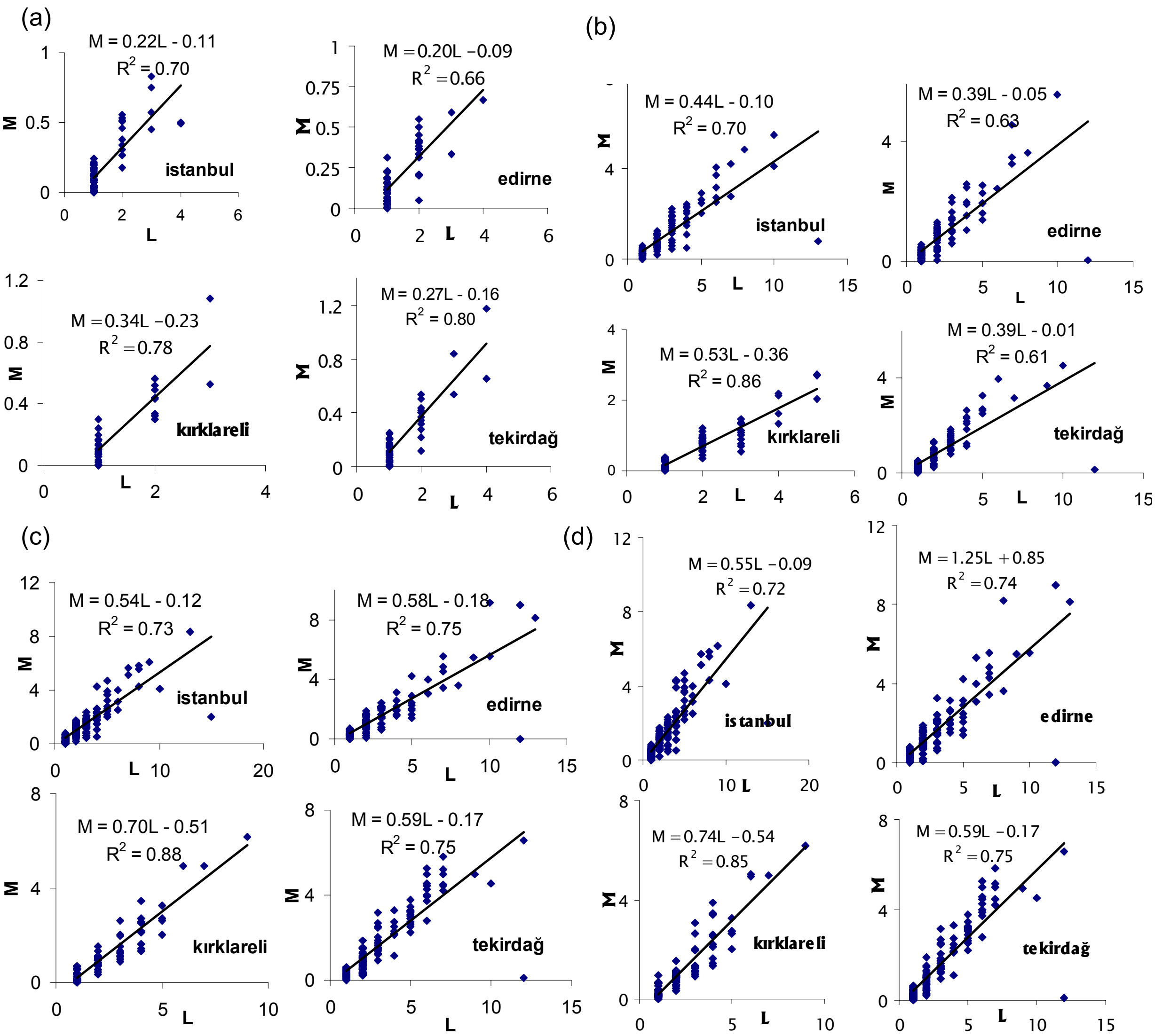

Fig. 4 Magnitude–duration curve at truncation level (a) 0.5, (b) –1, (c) –1.5, and (d) –2.

duration result in increased drought magnitude. Similar graphs can be obtained for other truncation levels. The only expected difference will be in the slopes of the relationships, which are almost equivalent to straight lines that pass almost through the origin.

Maps of *M*, *L*, and *I* are presented in Figs 5–7. The main purpose of this graphical approach is to combine three different, but related variables and examine their common behaviour in a two-dimensional domain as contour maps. In addition, linear model relationships are derived between two variables. These relationships facilitate discussion and in depth analysis. In this study, least-squares analysis and kriging are used for different goals. First, the least-squares method is used to a find linear equation and then a third set of variables, run analysis values, are taken into account and used as a base map in the kriging approach. This approach not only gives some climatic variations but also allows one to estimate drought intensity depending on precipitation (Sırdaş, 2002).

Drought magnitude increases with truncation level and has small values in Kırklareli, which is located at the centre of the Trakya region. Drought magnitude

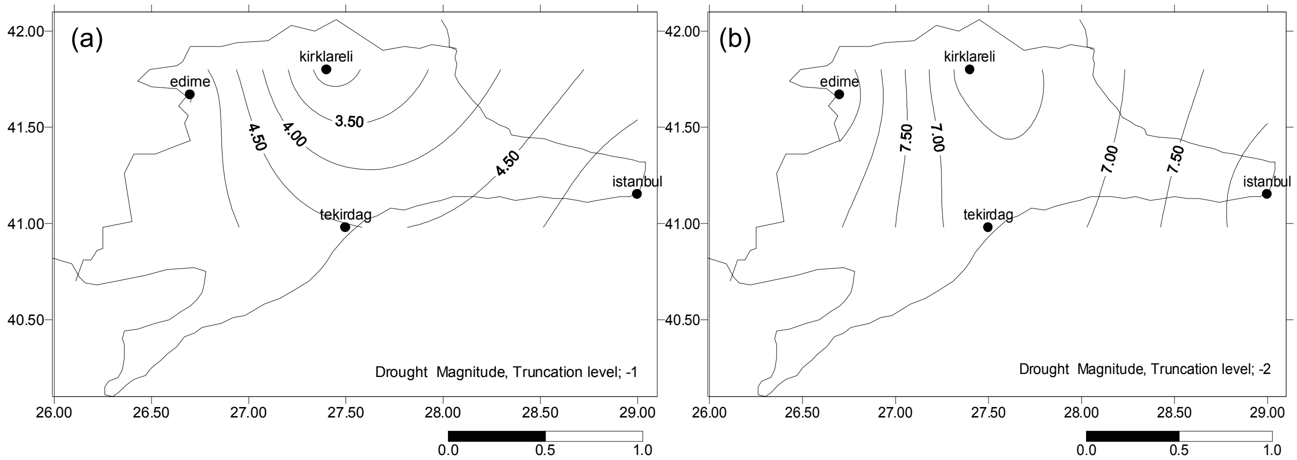

Fig. 5 Map of drought magnitude at truncation level (a) –1 and (b) –2.

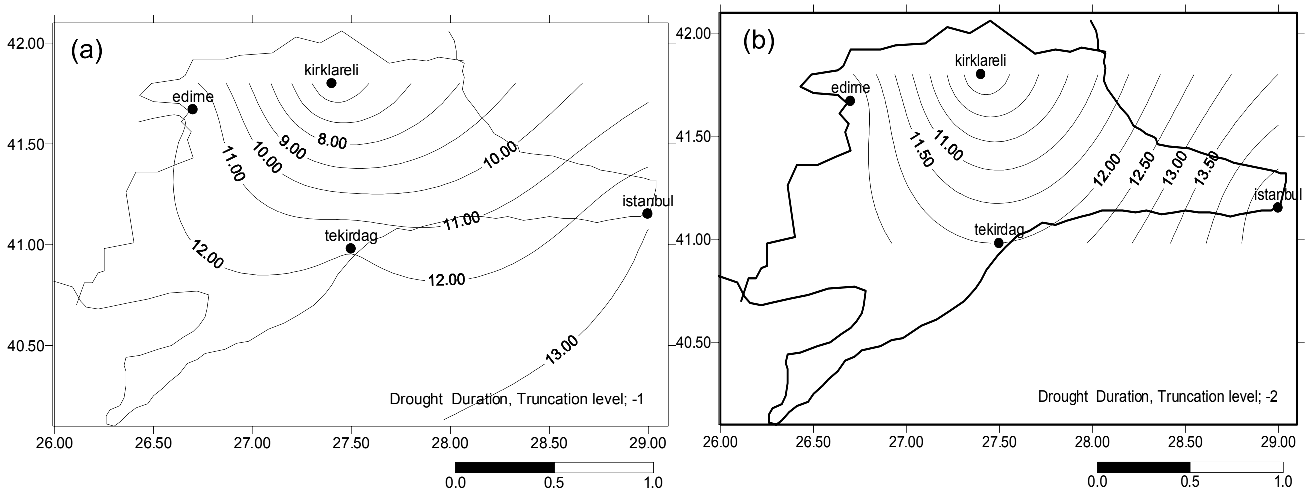

Fig. 6 Map of drought duration at truncation level (a) –1 and (b) –2.

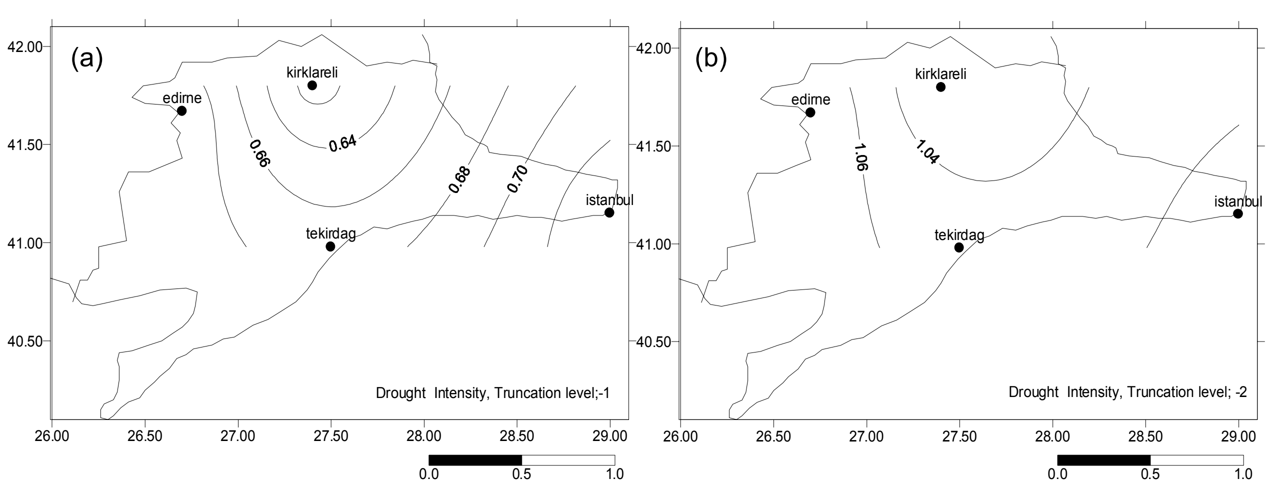

Fig. 7 Map of drought intensity at truncation level (a) –1 and (b) –2.

depends on the amount of precipitation and Kırklareli (total annual average precipitation: 328.58 mm) receives less precipitation compared to the other stations (İstanbul: 568.78 mm; Tekirdağ: 486.48; and Edirne: 493.51 mm). If the precipitation and fluctuation time series have small values, the standardization time series will also be small,, as will the characteristics of drought magnitude and intensity. Drought magnitude values are greater in the western and eastern parts of the Trakya region (Fig. 5). The maps show that drought duration is also longer in the eastern and western parts of the Trakya region, for example 11–12 months, but is shorter in Kırklareli (Fig. 6). Drought intensity in this region shows the same characteristics (Fig. 7): it has a value greater than 1 at a truncation level of –2. This is because drought magnitude increases with truncation level and drought intensity has a linear relationship to drought magnitude.

CONCLUSION

Run analysis and *z*-scores are commonly used for the identification of various drought characteristics, such as duration, magnitude, and intensity at different standard truncation levels. Basic formulae are given for these drought features and their applications are presented for precipitation records from İstanbul, Tekirdağ, Edirne and Kırklareli in northwestern Turkey. The relationships between drought duration and magnitude are provided in the form of scatter diagrams with the best straight-line fits. These are obtained for different truncation levels of –1, –1.5 and –2. Maximum severe duration and maximum extreme duration are both 15 months. In real-time drought monitoring across Turkey, it is recommended that all the major precipitation stations be treated with *z*-score calculations; later, the averages, minima and maxima of these drought descriptors should be mapped in order to identify areally the drought-affected and wet areas with a view to transferring water from wet to dry regions. For this purpose, the data should be collected without delay, so that the run analysis and *z*-score methodology can be regionally applied.

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