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Spatially heterogeneous drought analysis theory and future trends

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SUMMARY

Most often drought analysis methodologies are based on point-wise time series record assessments with very specific local conclusions, but their areal, regional and in general spatial properties are examined to a lesser extent. This paper will provide general description of droughts in addition to the regional methodological approaches with rather simple but innovative manner. The study area is thought as composed of a set of sub-areas each with different dry (wet) period probabilities. In general, heterogeneous region has different probability of dry(wet) spell occurrence at each sub-area. In fact, whenever the probability at each sub-area is not equal to any other sub-area, it corresponds to heterogeneous region. The areal cover probability (ACP) of the region is derived by considering the point-wise probabilities on the assumptions that the occurrences of dry (wet) spells are mutually exclusive, independent with heterogeneous probability patterns. Additionally extreme value probabilities of areal drought coverage are derived for heterogeneous sub-area probabilities. All of the heterogeneous drought probability expressions reduce down to homogeneous case provided that sub-areal probabilities are equal to each other. The methodology presented in this paper paves ways for more realistic drought phenomenon spatial probability of occurrences when the sub-areal dry spell probabilities are dependent on each other but heterogeneous.

1. Introduction

Droughts are among the rare events related to water availability and people start to feel them when there is not enough water. Drought periods may correspond to scarce rainfall events, excessive runoff exploitation, and groundwater abstraction more than safely rechargeable amounts from the rainfall after each runoff. When drought comes everybody is concerned, if it lasts everybody tries to do their best for the combat but when it passes away everybody forgets except those who have been hurt (Yevjevich et al., 1983).

The effects of drought accumulate slowly over a considerable period of time, and may linger for many years after the termination of the event (Wilhite, 1996). Drought impacts are less obvious and spread over larger areas than are damages that result from other natural hazards such as floods, earthquakes, volcanoes, etc. Consequently, dry (wet) spell impact quantification and provision are far more difficult task than other natural hazards. It is, therefore, necessary to seek help from probabilistic and statistical approaches and as their overall combinations from the stochastic evaluation methodologies and models in their quantification for the purpose of temporal, spatial or spatio-temporal predictions (Şen, 1980a,b).

Majority of the analysis has concentrated on temporal assessments. The first classical approach to statistical analysis of droughts (dry spells) and floods (wet spells) has been about the evaluation of instantaneously smallest value in a measured sequence of basic variable such as precipitation recorded at a single site (sub-area), (Gumbel, 1963). This method gives information on the maximum value of dry and wet spell duration magnitude with 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 Downer et al. (1967), Llamas and Siddiqui (1969), Saldarriaga and Yevjevich (1970), Millan and Yevjevich (1971), Guerrero-Salazar (1973), Guerrero-Salazar and Yevjevich (1975), Şen (1976, 1977, 1980a) Şen and Boken (2005) and brief descriptions by Dracup et al. (1980).

Due to the analytical difficulties, the study of regional dry and wet spells has been studied in a relatively smaller extent. The first study along this line is due to 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 random field concept. However, these studies are limited in the sense that they investigate regional patterns without temporal considerations. Panu and Sharma (2002) gave perspectives and challenges for future drought studies and they also made critical review of the existing literature. Mishra et al. (2009) have investigated alternative renewable process and run theory for drought interval time distribution, mean drought inter-arrival time, joint probability distribution function Chung

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and Salas (1999) have proposed low-order discrete autoregressive moving average and transition probabilities of drought events. Furthermore, Mishra and Singh (2010) gave an extensive review of drought phenomenon by considering many journal papers. So far, many researchers focused on the occurrence of drought events, particularly their duration by using the concept of runs. The probability distribution of drought occurrence, expected values and variances of first arrival and inter-arrival times of drought events, and the associated risks are derived. Recently, another approach appears as the copula functions, which are applied in bivariate drought in drought duration and severity frequency analyses (Lee et al., 2012).

In all the previous studies the spatial sub-area (site) spells are assumed as homogeneous (equal probability of occurrences). The main purpose of this paper is to provide dry and wet spell duration assessments based on temporal regional probabilistic modeling, where each sub-area is assumed to have different wet and dry spell occurrence probabilities, i.e. heterogeneous probabilities. For this purpose, the general spatio-temporal drought model is developed based on the assumptions that regional dry and wet spell occurrences are mutually exclusive, independent but heterogeneous. In the literature the simplest model of homogeneity exists with all other assumptions remaining the same. The general expression of this paper reduces to the available homogeneous Bernoulli trial case.

2. Drought definitions, types and impacts

Due to extended period of time drought is regarded as a kind of climate departure from normal climatic conditions in an area. Glantz (2003) state that drought is a normal part of climate, rather than a departure from normal climate. In such it is complicated to control as a rare and random occurrence depending on many social, economic and engineering aspects. Hence its avoidance needs sound scientific approaches and methodologies, which should provide a firm basis for the drought combat policy and decision making process so as to minimize its hazardous consequences on human and living creature life. This perception has typically resulted in little effort being targeted toward those individuals, population groups, economic sectors, regions, and ecosystems most at risk (Wilhite, 2002). Improved drought policies and preparedness plans that are proactive rather than reactive and that aim at reducing risk rather than responding to crisis are more cost-effective and can lead to more sustainable resource management and reduced interventions by government (Wilhite and Svoboda, 2000). In general hazard is use to describe the natural aspects of drought phenomenon and disaster expresses negative impacts on human and environmental situations. Long durations of rainless spells may not give the impression that there is an ongoing drought until the crops have withered and died. One cannot be sure about the end duration unless there are good indications for this.

Wilhite and Glantz (1985) have classified drought definitions as conceptual, i.e., relatively vague (fuzzy) and operational which is meant to provide specific guidance on aspects of onset, severity and termination. The latter descriptions are among the objective quantities that are frequently asked about in any drought study. These are; when is the starting time of drought? How severe is the drought? and when is the termination time of the drought? In fact, the time difference between the termination and starting instances shows the duration of drought.

Although many areas were prone to drought risks all over the world, unfortunately the drought existence and appearance have been vague, imprecise, uncertain and most of the time fuzzy not only for the common people but also for the experts in the area. It is, therefore, difficult to find a unique definition for droughts, and consequently, the current definitions are rather based on expert and professional concepts. In order to alleviate the case, most often droughts are classified right from the beginning according to their attachment of economic consequences and physical causes. Even though droughts inflict economic losses but they are social phenomena as well. Any drought that may give rise to human starvation then it is a famine. These drought types are shown simply in Fig. 1.

Meteorological droughts can be converted to numerical objective values through some formulations and the most famous as well as widely used alternative is the Palmar Drought Intensity Indicator (Palmer, 1965). According to this criterion for drought classification in an area it is necessary to have monthly and few or several year precipitation and temperature records in addition to soil moisture balance. This shows that objectively the meteorological drought cannot be expressed by precipitation records only but additionally consideration of temperature also. The drought duration, intensity and frequency are all interrelated in an area (Sırdaş and Şen, 2003).

Agricultural drought and crop yield predictions are unsuccessful without long term climate predictions (Şen and Boken, 2005). Furthermore, agricultural drought occurs when a moisture shortage lasts long and hits hard enough to negatively impact cultivated crops. Soil conditions, groundwater levels, and specific characteristics of plants also come into play in this functional definition of drought. A combined effect of all these types may cause undesired reflections in social life of a region and hence they are referred to as social droughts. The most significant components that are involved in each one of the drought type are given separately in Fig. 2.

On the other hand, Fig. 3 presents the consequences that can appear after each drought type.

Economic consequences of droughts are more important for humid regions because of unpreparedness of people to recurrent drought events and the large investments in agriculture may undergo large losses from droughts. Economic losses caused by droughts are mainly the reduction in the production of crops, cattle, industrial goods, poor navigation and hydro-power.

Among the spatial effects of droughts are soil erosion and consequent dust storms, forest fires, plant diseases, insect plagues, decrease of personal and public hygiene, increased concentration of pollutants, degradation of water quality, harmful effects on wildlife, and deterioration in the quality of visual landscape.

3. Definitions of basic probabilities

Under given specific circumstances drought has a single value at each time instant and small sub-areas. Such a space–time distribution is referred to as a field quantity. Since drought quantities cannot be predicted with certainty they are assumed to be random and hence, it is necessary to study a new class of fields, i.e., random fields, $\xi(s, t)$ as a random function at a point, s, (like a pixel) and time, t. The values $\xi(s, t)$ are subject to certain probability laws. A complete description of a random field can be achieved by constructing all the finite dimensional probability distribution functions (pdf) of the field at different points in time and space.

In this paper precipitation phenomenon is modeled as a random field where instantaneous time-wise probability at a set of sub-areas over the study region is referred to as the areal coverage probabilities (ACP). It is a conditional pdf being conditioned by whether at least one dry spell occurs in the sub-area during a

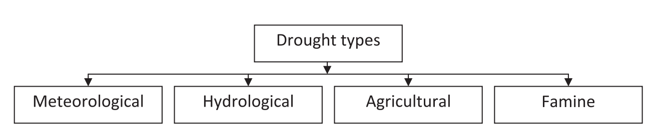

Fig. 1. Drought types.