Sayı (Number): 4

SU VAKFI

Modeling of Agricultural Droughts

Tarım Kuraklıklarının Modellenmesi

Zekâi Şen

Nisan (April) 2017
İstanbul - Türkiye

KURAKLIK KÜLLİYESİ
TURKISH WATER FOUNDATION
DROUGHT FACULTY

KURAKLIK BÜLTENİ : SAYI 4

Modeling of Agricultural Droughts

Tarım Kuraklıklarının Modellenmesi

Zekai ŞEN

Basıma Hazırlayan :
Muhiddin YENİGÜN

SU VAKFI

SU VAKFI

Libadiye Cad. Doğanay Sokak No:6 Kat:4 Üsküdar İstanbul
Tel: (216) 412 3383 - Faks: (216) 412 3390
suvakfi@suvakfi.org.tr - www.suvakfi.org.tr

Modeling of Agricultural Droughts

Zekai Şen

Abstract

Among different and interrelated drought occurrences, agricultural droughts are most significant because they affect the crop yield, and subsequently food demand may be inflicted harmfully due to food deficiency within a region or society. Drought-induced natural disasters such as agricultural types have increased recently in number of occurrences, temporal and spatial extensiveness during the last 5 decades due to anthropogenic and natural unexpected developments such as the global warming implying greenhouse effect and precipitation deficiency. Many countries have set up national drought preparedness plan in the expectation of reducing societal vulnerability to drought through the adaptation of preventive, anticipatory policies and programs. Although drought prone countries all over the world may have different causal effects, the drought evaluation methodologies are common irrespective of geographical locations. It is, therefore, necessary to elaborate on different drought and hazard assessment methodologies on a scientific basis, so as to be useful to all concerned parties whether agriculturalist, hydrologist, meteorologist, researcher and administrators. This paper provides temporal and spatial probabilistic modeling of agricultural droughts, which are useful for temporal and spatial drought risk predictions and parameter assessments.

Key Words: Agriculture, droughts, model, parameters, probability, risk, temporal, spatio-temporal.

INTRODUCTION

The questions similar to how extensive is the drought in agricultural areas, in general, and what are their effects in the wheat, cotton, etc. areas, in particular are very common among the governmental and farmer circles. ''What portion of the cotton belt will be affected by the coming possible drought due to surplus moisture?'' is another question that must be answered based on various information sources concerning regional weather, climatology, soil conditions crop type and groundwater conditions. Generally, local differences in soil and crop types, root zone extensions, crop development stage and precipitation amounts are among the drought evaluation factors. For instance, the meteorological information only may provide useful source of data for the assessment of questions like what is the crop moisture situation in the soybean producing regions.

From a certain point of view, agricultural drought may be defined in its simplest form as a transpiration deficit. Droughts may be regarded as normal, recurrent features of climate for virtually all climatic regions. It is not restricted to only low precipitation regions of the world, but occasionally high precipitation areas may also experience drought occurrences. It is, therefore, necessary to distinguish drought from the aridity which is restricted to low rainfall regions and is a permanent climatic feature like in the arid regions of the world. The character of droughts is not only temporal as most of the people understand, but more severely spatial relating unique meteorological, hydrological, agricultural, and socioeconomic characteristics of the region concerned. From the agricultural point of view, first of all droughts are related to relatively long-term average conditions of balance between precipitation and, especially, evapotranspiration in a particular area. Droughts differ from other natural hazards in several ways. First, it is a creeping phenomenon making its onset and end difficult to even feel. The effects of drought accumulate slowly over a considerable period of time, and may linger for years after the termination of the event (Wilhite, 1996). On the other hand, drought impacts are less obvious and spread over a larger graphical area than are damages that result from other natural hazards such as floods, earthquakes, volcanoes, etc. Consequently, drought impact quantification and provisions are far more difficult task than other natural hazards. It is, therefore, necessary to seek help from probabilistic, statistical approaches and as their overall combinations from the stochastic evaluation methodologies and models in their quantification for the purpose of temporal and areal predictions. These techniques are helpful in cases where the lack of a precise and objective definition occur in specific situations. Especially, the lack of precise and objective definition as well as incomplete data are the main obstacles in proper understanding of drought and its modeling, and subsequently this led to indecision and incapability in action against the droughts on the part of managers, policy makers, and others. The main drought causes are concerned more with the effects of precipitation shortfall periods on surface or subsurface water supply in addition to streamflow, reservoir, lake and groundwater levels, rather than with precipitation shortfalls. Especially, during the agricultural droughts, competition for water escalates and conflicts arise between water users significantly. In general, upstream changes in land use such as deforestation and changes in cropping patterns may alter runoff and especially, infiltration rates which may lead to frequent and severe agricultural drought. On the other hand, socioeconomic dimension of drought associates the supply and demand of some economic good with elements of meteorological, hydrological and agricultural droughts.

There is no procedure so far for predicting accurately the time occurrence of drought durations or areal drought extensions. Although in the past various subjective approaches were employed for drought estimations, they all ended in surprising failures. In modern times, drought estimations are sought on the basis of objective and systematic scientific procedures and along this line the probability theory and statistics provide a convenient procedure for drought occurrence predictions. These techniques, in general, are used for depicting the quantitative relationships between the weather variables and the drought characteristics. For instance, the multiple regression analysis or Monte Carlo simulation techniques are used to answer questions concerning regional and temporal drought frequencies.

Majority of the drought analysis has concentrated on temporal assessments. The first classical approach to statistical analysis of droughts has been about the evaluation of instantaneously smallest value in a measured sequence of basic variable such as SMC recorded at a single site, (Gumbel, 1963). This method gives information on the maximum value of drought 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) and brief descriptions by Dracup et al (1980). Due to the analytical difficulties, the study of regional droughts has been carried out to a relatively smaller extent. In fact, 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 drought patterns without temporal considerations.

In the following sequel, a systematic approach is presented for the calculation of temporal and regional drought occurrences by simple probability procedures and then their numerical solutions. Recent improvements in statistical methods have even tended to place a new emphasis on rainfall studies, particularly with respect to a better understanding of persistence effects (Şen, 1989, 1990). In fact, the persistence is used to estimate possible durations of dry periods.

The main purpose of this paper is to provide agricultural drought assessments based on probabilistic modeling both temporally and spatially. The implementation of these modeling techniques is quite straight forward provided that basic probabilities of soil moisture content deficit and surplus are defined on the basis of soil moisture content observations.

Agricultural Droughts

Agricultural products are necessary for the sustenance of any society for healthier future developments. The very basis of the agriculture is related to food production which is the essential basic human life requirement for survival. Unfortunately, today there are millions of people suffering from famine which is one of the extreme cases of agricultural drought in many parts of the world, especially in the African continent. Although one of the main causes is due to overpopulation, many other parts of the world are suitable for excessive agricultural products which may serve to drought and famine stricken areas of the world. With a better manner of combat against the agricultural drought in many parts of the world, it is possible to improve agricultural production. It is necessary to know the definition of agricultural drought prior to any modeling study. Agricultural droughts are concerned with the growth phases of plants which start with sowing and end with harvest activities. Any deficiency in the soil moisture content (SMC) leads to wilting and then insisting drought periods are dangerous for the plant growth and consequent beneficial harvesting. Agricultural droughts create water stress in the plants, and consequently, there is water deficit period which destroys internal metabolic activities leading to morphological modifications. The water stress continues until the roots are recharged by soil moisture after useful precipitation occurrences, and this period of water stress is referred to as the agricultural drought. Depending on the intensity and duration of agricultural drought production, quality deteriorates and production amount reduces. During the agricultural drought seed yield decreases due to CO_2 assimilation (Şaylan, et al. 2000).

Although the effect of water deficit on various plants is different from each other, their common reactions in the plants are the same. Water deficit causes stagnation in the polenization with resulting wilting of leaves and consequently, young unripe fruits fall down from the plants. In the latest stages of the stress with the closure of voids on the leaves, photosynthesis occurs at lower rates than normal, and hence, leaves start to fall (Hsiao, 1992). Since the agricultural drought gives rise to reduction in the plant production, this unwanted effect can be alleviated by irrigation with sufficient water supply. In recent years, for the improvement of production, various plant-climate models are used through computer simulations. One of such models is set up for establishing rational relationships between the plant, soil and atmospheric phenomena and referred to as SIMWASER model at the Technical University of Berlin, Institute of Plantculture (Wolkewits and Stenitzer, 1976).

Agricultural droughts are important because of the implications for food production. All land types whether arable or pastoral rely ultimately on the water availability for plant growth in the soil. This is the reason why agricultural drought occurs in the case of insufficient soil moisture in order to maintain average crop growth and yield. It is, therefore, logical to base agricultural drought indices on soil moisture measurements where water balance studies are necessary. At regional, national and international levels, the most visible consequences of agricultural droughts are in the reductions of crop output, i.e. harvest. Severe agricultural droughts may lead to livestock slaughtering, the recovery of which might take several years after the drought cessation. In extreme agricultural drought occurrences, significant disruptions may appear in world food commodities. The greatest disaster that may arise as a consequence of especially agricultural droughts is famine which is a cultural phenomenon. To some extent, it could be argued that famine is merely an extreme expression of agricultural drought which reduces the food supply sufficiently to cause starvation.

Drought Risk Assessment

Generally, risk is defined as the probability of undesirable event and it is an integral part of life. In any natural phenomena such as droughts, risk cannot be eliminated completely but there are different scientific approaches and methodologies for its management. The analysis of risk is based on mathematical theories of probability and scientific methods of stochastic processes for identifying causal links between different types of hazardous activities, and consequent, adversities. According to Kates and

Kasperson (1983), risk assessment comprises three distinct steps:

a) an identification of hazards likely to result in disasters, i.e. what hazardous events may occur?
b) an estimation of risks of such events, i.e. what is the probability of each event?
c) an evaluation of social consequences of the derived risk, i.e. what is the loss created by each event.

In this chapter, as a disastrous event, agricultural droughts will be adopted, and the temporal and spatial probabilistic statements for the occurrence of these events will be derived probabilistically. A knowledge of the magnitude and probable frequency of occurrence is a vital element in further compound calculations in the drought occurrences. Drought descriptor parameters are all dependent on the probability distribution function (PDF) of drought durations.

DROUGHT FEATURES

Conceptual definition of agricultural drought implies statistical chance combinations of persistently recurrent rainfall events. SMC deficit which is also referred to as dry spell can be expressed in terms of rainfall deficit period of basic time intervals as hours, days, weeks, months and years. Most often, in the agricultural drought assessments, monthly dry and wet spells play significant role in the crop yield equations. However, for long-range drought estimations annual basic periods are taken into consideration. It is well known from the behavior of rainfall phenomena that short basic times include non-stationary i.e. dynamic but longer periods have stationary behaviors. The most of the drought prediction modeling formulations on the basis of probability, statistics and stochastic approaches, the assumption of stationary is taken as a fundamental assumption. Therefore, these formulations cannot be reliable until the natural phenomenon is stationary and evolves along the time axis.

Similar considerations can be thought about the regional behavior of droughts, but in this case homogeneity or heterogeneity of the areal extent comes into view. If each subarea of the drought stricken 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 modeling. From a climatic viewpoint, agricultural droughts have frequent quasi-cyclical events and such periodicities are usually difficult to preserve in models, lack suitable explanations and have rather low predictive utility. In order to achieve successful predictability, it is necessary to have records of basic data including rainfall, climate, hydrology and SMC.

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

1. A wet spell occurs when any time series value at 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 SMC surplus,
2. Otherwise, a dry spell takes place as $(X_i < X_0)$. Accordingly, the difference $(X_0 - X_i) < 0$ is the SMC deficit.
3. 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 agricultural problem in plant growth. 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),

4. Similarly, if a sequence of dry spells is preceded and succeeded by a wet spell, it is then referred to as the duration of dry period which might give rise to problems during the phonologic phases, such as vegetative critical and harvesting phases of plant growth. 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),
5. If a dry spell (SMC deficit) is followed by a wet spell then there is a transition from the drought period to wet period (SMC surplus), i.e., (X_i<X_j),
6. Similarly, if a wet spell is followed by a dry spell then there is a transition from the wet period to drought period, (X_i>X_j),
7. The maximum dry duration in the record of past SMC observations corresponds to the most critical agricultural drought period that has occurred in the history of the record site. Such a critical period is directly related to the critical phase among the phonological phases and it is important in crop yield evaluations.
8. The summation of water deficits during the whole drought period gives the total drought severity. This is equivalent to accumulation of SMC needed to offset the agricultural drought which is, in turn, directly related to rainfall excess. Finally, the division of this accumulated SMC by drought duration shows the average of agricultural drought severity.

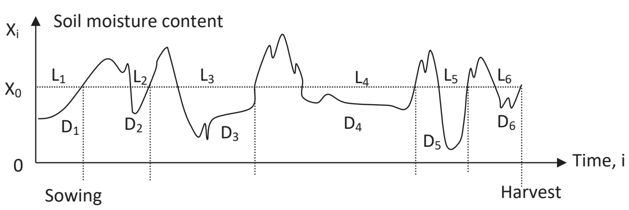


Figure 1. Objective drought quantities

In the context of uncertainty techniques, it is possible to calculate almost all objective drought quantities statistically or probabilistically provided measured 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 which are also referred to relative frequency diagram with its theoretical counterpart as probability distribution function (PDF). On the other hand, if the interest lies in the drought frequency of occurrence, then the probability statements can also be calculated from the same record. For instance, $\mathbf{P(X_i>X_0)}$ and $\mathbf{P(X_i<X_0)}$ express simply the SMC surplus and deficit basic probabilities, respectively. These basic probabilities help to construct a probabilistic model which may be used in predicting agricultural drought durations (Şen, 1976).

TEMPORAL DROUGHT MODELS

Statistical theory of runs provides a common basis for the objective definition and modeling of critical drought given a time series (Feller, 1967). Simply a constant truncation level SMC divides the whole series into two complementary parts, those greater than the truncation level, which is referred to as the positive run in statistics, SMC surplus spell in agricultural sense and similarly a negative run or SMC deficit spell. He also gave a definition of runs based on recurrence theory and Bernoulli trials as follows. A sequence of n events, **S** (success, SMD surplus) and **F** (failure, SMC deficit), contains as many **S**-runs of length **r** as there are non-overlapping uninterrupted blocks containing exactly **r** events **S** each. This definition is not convenient practically, because it does not say anything about the start and end of the run, i.e. drought. On the other hand, a definition of runs seems to be most revealing for the analysis of various drought features since a run is defined as a succession of similar events preceded and succeeded by different events with the number of similar events in the run referred to as its length (see Figure 1).

Independent Bernoulli Model

Truncation of a SMC series X_i **(i = 1,2,...,n)** at a constant level yields two complementary and mutual distinct events, namely, a SMC surplus $X_i > X_0$ and SMC deficit $X_i < X_0$ with respective probabilities **p** and **q=1-p**. If the probability of the longest run-length **L** , i.e. critical agricultural drought duration, in a sample size of **i** is equal to **j** and it is denoted by $\mathbf{P_i\{L=1\}}$, then for sample size **i=1** one can simply deduce,

$$\begin{aligned} P_1\{L=0\} &= q \\ P_1\{L=1\} &= p \end{aligned} \qquad (1)$$

Herein, the first statement is simply the elementary probability of soil moisture deficit whereas the next one is the probability of SMC surplus. Since, the occurrences of the elementary events are assumed independent from each other then the combined probabilities for **i=2** can be written as,

$$\begin{aligned} P_2\{L=0\} &= P_1\{L = 0\}q \\ P_2\{L=1\} &= P_1\{L = 1\}q+P_1\{L = 0\}p \\ P_2\{L=2\} &= P_1\{L = 1\}p \end{aligned} \qquad (2)$$

Simply, $\mathbf{P_2\{L=0\}}$ indicates a SMC deficit followed by another SMC deficit. The first term on the right hand side in $\mathbf{P_2\{L=1\}}$ represents the SMC surplus followed by SMC deficit and the second term vice versa. Finally, $\mathbf{P_2\{L=2\}}$ is the combination of SMC surplus followed by another SMC surplus event. It is possible to develop the same probability concepts for a SMC time series of length **n** as (Şen, 1980a)

$$\begin{aligned} P_n\{L=0\} &= P_{n-1}\{L=0\}q \\ P_n\{L=j\} &= P_{n-1}\{L=j\}q + \left\{P_{n-1}\{L=j-1\} - \sum_{i=1}^{k_1} P_{n-i-1}\{L=j-1\}qp^{i-1}\right\}p + \sum_{i=1}^{k_2} P_{n-i-1}\{L=j\}qp^{j} \\ P_n\{L=n\} &= P_{n-1}\{L=n-1\}p \end{aligned} \qquad (3)$$

where **0<j<n** and $\mathbf{k_1=min(n-j,j-1)}$ and $\mathbf{k_2=min(n-j-1,j)}$. Herein, $\mathbf{P_n\{L=j\}}$ means the probability of agricultural critical drought of duration **j** in **n** time units (days, months or years).

Dependent Bernoulli Model

In the derivation of drought probabilities above, the occurrence of successive SMC deficit and surplus spells are considered as independent from each other. However, in nature, there is a tendency of SMC deficit (surplus) to follow SMC deficit (surplus) spell which implies dependence between successive occurrences. The simplest representation of dependence can be achieved by considering the relative situation of two successive time intervals. This leads to four possible outcomes as transitional probabilities which are referred to also as conditional probability statements in the probability theory. For instance, **P(-/+)** implies the probability of SMC deficit (-) at current time interval on the condition (given) that there is SMC surplus (+) in the following time interval. On the other hand, according to the joint probability definition, it is possible to state that (i) transition from SMC surplus to a SMC surplus with probability **P(+/+)**; (ii) transition from a SMC surplus to a SMC deficit with probability **P(-/+)**; (iii) transition from a SMC deficit to a SMC surplus with probability **P(+/-)**; and finally, (iv) transition from a SMC deficit to a SMC deficit with probability **P(-/-)**. Four SMC joint probability statements are **P(+,+)=P(+/+) P(+)**; **P(-,+)=P(-/+)P(+)**; **P(+,-)=P(+/-)P(-)** and **P(-,-)=P(-/-)P(-)**. Similar to independent Bernoulli case there are two state probabilities, namely, SMC surplus **P(+)** and SMC deficit **P(-)** probabilities. Since, transition and state probabilities are independent from each other then the relationships between them can be written as

$$P(+) = P(+/+)P(+) + P(+/-)P(-)$$
$$P(-) = P(-/+)P(+) + P(-/-)P(-)$$

where the first statement is the probability of SMC surplus in the current time interval with its first right hand side term as the probability of SMC surplus **P(+)**, in the previous time interval with its transition **P(+/-)** to current state from SMC surplus to SMC surplus, and the second term on the right hand side representing the transition **P(+/-)** from the SMC deficit case **P(-)**, in the previous time interval to SMC surplus in the current time interval. The next statement has similar interpretations. Furthermore, due to the mutually exclusiveness of probabilities the following sequences of probability statements are also valid. The first statement implies that any time interval should have either SMC surplus or SMC deficit cases; the second and third statements are valid for two successive time intervals. Hence, the second statement states that transition to the next interval is possible as SMC surplus or SMC deficit given that in the previous interval the state is in SMC surplus. The derivation mechanism of agricultural drought probabilities are the same as independent Bernoulli case but a slight change of notation is necessary due to the dependence nature of the successive events. Hence, the probability of the longest critical drought duration **L** being equal to an integer **j** value in a sample size of **i** with a surplus state at the final stage will be denoted by $P_i^+\{L=j\}$. Similar to equation (1) with these new notations one can write,

$$\begin{aligned} P_1^-\{L=0\} &= P(-) = q \\ P_1^+\{L=1\} &= P(+) = p \end{aligned} \qquad (4)$$

If two successive time intervals **(i=2)** are considered then by enumeration, it is possible to obtain,

$$\begin{aligned} P_2^-\{L=0\} &= P_1^-\{L=0\}P(-/-) \\ P_2^+\{L=1\} &= P_1^-\{L=0\}P(+/-) \\ P_2^-\{L=1\} &= P_1^+\{L=1\}P(-/+) \\ P_2^+\{L=2\} &= P_1^+\{L=1\}P(+/+) \end{aligned} \qquad (5)$$

The first and third statements are for the SMC deficit occurrences in the second interval. In the first statement, the transition is from SMC deficit to SMC deficit whereas in the third statement, it is from SMC surplus to SMC deficit. In general, if the sample size is **i**, then

$$\begin{aligned} &P_i^-\{L=0\} = P_{i-1}^-\{L=0\}P(-/-) \\ &P_i^+\{L=j\} = \sum_{m=0}^{k_1} P_{i-j}^-\{L=m\}P(+/-)P^{j-1}(+/+) + \sum_{m=1}^{k_2} P_{i-m}^-\{L=j\}P^{m-1}(+/+) \\ &P_i^-\{L=j\} = P_{i-1}^+\{L=j\}P(-/+) + P_{i-1}^-\{L=j\}P(-/-) \\ &\qquad \text{if } i-1=j \text{ then } P(-/-)=0 \\ &P_i^+\{L=i\} = P_{i-1}^+\{L=i-1\}P(+/+) \end{aligned} \qquad (6)$$

where $\mathbf{k_1=min(i-j-1,i)}$ and $\mathbf{k_2=min(i-j-1,j-1)}$. The numerical solutions of these equations on computers for different sample sizes are presented in Figure 2 on the basis of SMC surplus probability as **p**=0.7. It is possible to read from this graph critical agricultural drought occurrence of a given duration within given number of samples. For instance, what is the agricultural drought of 10 year duration occurrence within 50 years? In order to answer such a question, first enter the horizontal axis in Figure 2 with **L**=10 and draw a vertical line until **n**=50 curve is intersected and finally, read the probability value corresponding to this intersection on the vertical axis. Such a procedure leads to about 0.62. However, the same question for 100 years yields the critical agricultural drought probability as 0.43.

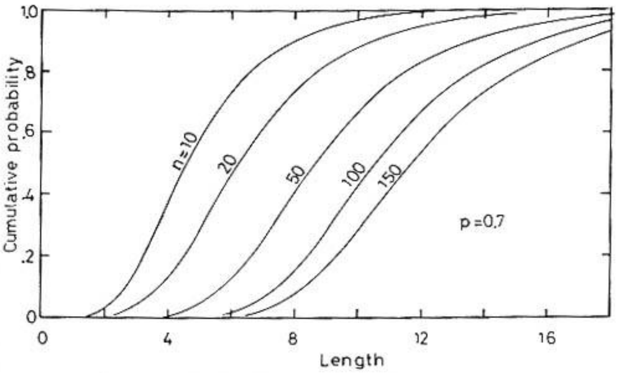


Figure 2. Critical drought

Markov Model

Although successive occurrence dependence between SMC surplus and SMC deficit events are accounted simply by dependent Bernoulli model but in nature dependences are more persistent than such a simple case. In order to model critical agricultural droughts more realistically herein the second order Markov processes will be presented. This process requires in addition to a two-interval basic also three-interval basic transitional probabilities. Again the SMC surplus and SMC deficit probabilities remain as they were in the previous models. The complete description of second order Markov model for critical drought probability predictions is presented by Şen (1990). In addition to already mentioned basic probability requirements in the previous models, the new set of transitional probabilities are among SMC surplus and SMC deficit occurrences along three successive time intervals which can be defined as eight ($i=2^3=8$) mutually exclusive and collectively exhaustive alternatives

$$\mathbf{P(+/++) = P(X_i>X_0, X_{i-1}>X_0, X_{i-2}>X_0)}$$
$$\mathbf{P(-/++) = P(X_i<X_0, X_{i-1}>X_0, X_{i-2}>X_0)}$$
$$\mathbf{P(+/+-) = P(X_i>X_0, X_{i-1}>X_0, X_{i-2}<X_0)}$$
$$\mathbf{P(-/+-) = P(X_i<X_0, X_{i-1}>X_0, X_{i-2}<X_0)}$$
$$\mathbf{P(+/-+) = P(X_i>X_0, X_{i-1}<X_0, X_{i-2}>X_0)}$$
$$\mathbf{P(-/-+) = P(X_i<X_0, X_{i-1}<X_0, X_{i-2}>X_0)}$$
$$\mathbf{P(+/--) = P(X_i>X_0, X_{i-1}<X_0, X_{i-2}<X_0)}$$
$$\mathbf{P(-/--) = P(X_i<X_0, X_{i-1}<X_0, X_{i-2}<X_0)}$$

Herein, the first statement indicates notationally, the probability of SMC surplus at current interval given that two successive intervals had both SMC surpluses. Others can be interpreted similarly. On the other hand, mutual exclusiveness implies that **P(+/+ +)+P(-/+ +)=1; P(-/-+)+P(-/+-)=1; P(+/-+)+P(-/-+)=1** and **P(+/--)+P(-/--)=1**.

The critical agricultural drought durations for the first two samples are the same as in the dependent Bernoulli case. However, when the sample size is three the relevant drought probabilities become

$$\mathbf{P_3(L=0/++)=P_2(L=0/+)P(+/++)}$$
$$\mathbf{P_3(L=1/-+)=P_2(L=0/+)P(-/++)+P_2(L=1/-)P(-/+-)}$$
$$\mathbf{P_3(L=1/++)=P_2(L=1/-)P(+/+-)}$$
$$\mathbf{P_3(L=1/+-)=P_2(L=1/+)P(+/-+)} \qquad \mathbf{(7)}$$
$$\mathbf{P_3(L=2/--)=P_2(L=1/+)P(-/-+)}$$
$$\mathbf{P_3(L=2/+-)=P_2(L=2/-)P(-/+-)}$$
$$\mathbf{P_3(L=3/--)=P_2(L=2/-)P(+/--)}$$

where $\mathbf{P_3(L=0/++)}$ is the probability that the critical drought duration will be equal to zero given that the two previous instants are in SMC surplus states. The critical drought duration probabilities are all dependent after sample size three on the combinations of two previous sample sizes and hence a recursive formulation can be obtained in general, for sample size **n** as,

$$\mathbf{P_n(L=0/++)=P_{n-1}(L=0/++)P(+/++)}$$
$$\mathbf{P_n(L=1/-+)=P_{n-1}(L=0/++)P(-/++)+P_{n-1}(L=1/+-)P(-/+-)+P_{n-1}(L=1/+-)P(-/+-)}$$
$$\mathbf{P_n(L=1/-+)=P_{n-1}(L=1/+-)P(+/+-)+P_{n-1}(L=1/+-)P(-/+-)}$$
$$\mathbf{P_n(L=1/+-)=P_{n-1}(L=0/+-)P(+/+-)}$$

$P_n(L=j/--)=P_{n-1}(L=j-1/-+)P(-/-+)+P_{n-1}(L=j/-+)P(-/-+)$

$P_n(L=j/-+)=P_{n-1}(L=j/++)P(-/++)+P_{n-1}(L=j/+-)P(-/+-)$

$P_n(L=j/++)=P_{n-1}(L=j/++)P(+/++)+P_{n-1}(L=j/+-)P(+/+-)$

$$P_n(L=j/+-)=P_{n-1}(L=j/-+)P(-/-+)+P_{n-1}(L=j/++)P(+/++) \text{ where } 2\leq j\leq(n-2) \quad (8)$$

$P_n(L=n-2/--)=P_{n-1}(L=n-3/-+)P(-/-+)$

$P_n(L=n-2/-+)=P_{n-1}(L=n-3/--)P(-/+-)$

$P_n(L=n-2/++)=P_{n-1}(L=n-3/+-)P(+/+-)$

$P_n(L=n-2/+-)=P_{n-1}(L=n-3/--)P(-/--)$

$P_n(L=n-1/+-)=P_{n-1}(L=n-1/--)P(+/--)$

$P_n(L=n/--)=P_{n-1}(L=n-1/--)P(-/--)$

Numerical solution of these equations is achieved through the digital computers and some of exemplary results are exhibited in Figures 3 and 4.

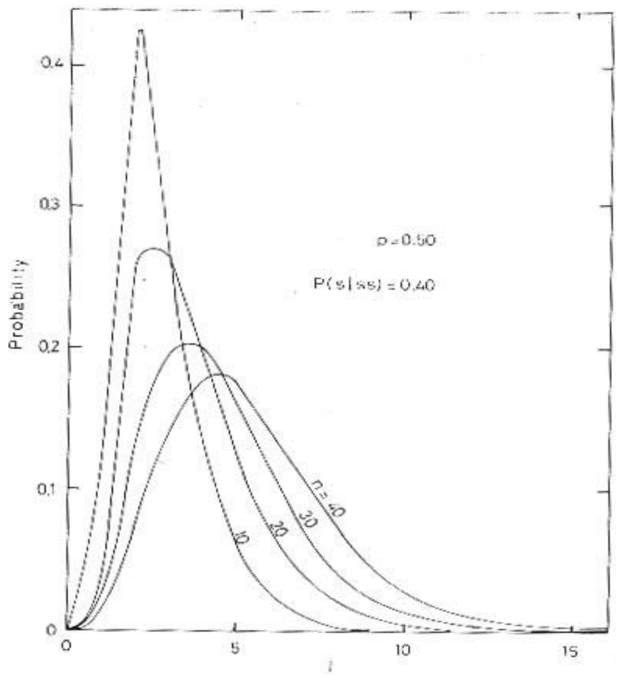


Figure 3. Critical drought duration distribution for different sample sizes at **P(+/+ +)** *= 0.40.*

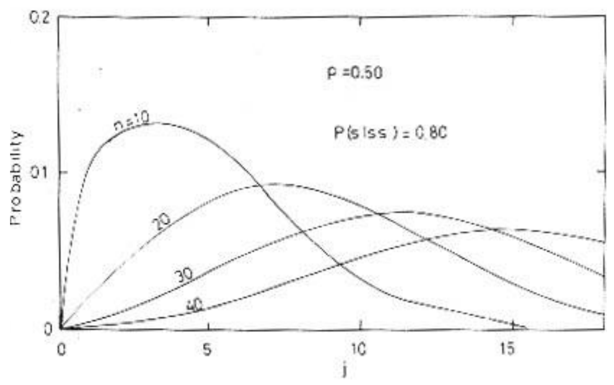


Figure 4. Expectation of the critical drought duration for different sample sizes and **P(+/+ +)** *= 0.8*

SPATIO-TEMPORAL DROUGHT MODELS

The models in the previous sections are useful in assessing drought features along time axis. However, agricultural droughts are extensive also regionally and at times cover areas of continental scales. Most often, droughts strike not only one country but many countries in different proportions. In literature, almost all the studies are confined to temporal drought assessment with few studies concerning areal coverage. The view taken in this section is to model both spatial (regional) and temporal drought behaviors by the same model simultaneously.

In order to model the coverage of drought occurrence patterns, the study area must be divided into characteristically distinctive and mutual exclusive subareas on the basis of prevailing agricultural and rainfall considerations. It is accepted generally that severe agricultural droughts arise as a result of apparent chance variations of the atmospheric circulation. Droughts are always initiated by a shortage of precipitation and many of the traditional approaches to drought definition have been restricted to rainfall analysis only (Smith, 2001). Simple assessment of drought severity depends largely on the magnitude and regional extent of precipitation deficiencies from mean climatic conditions. In the case of agricultural drought additionally weather, SMC and crop types must be considered. Since, precipitation is the main source for agricultural activities, it is one of the most dominant factors in subdivision of the whole region into different drought potentials. In addition, precipitation is the most easily available data than any other drought effective variables. For the sake of simplicity, the precipitation will be considered as one of the main variables which give rise to regional and temporal variations of droughts. Other major variables are especially SMC which varies regionally as well as temporally leading to dry and wet spells depending on human and agricultural activities.

In regional studies, clustering of dry spells in a region will be referred to as drought area otherwise wet area is valid. Herein, two different regional drought models will be explained. The first model relies on regional dry and wet areal spell probabilities, $\mathbf{p_r}$ and $\mathbf{q_r}$ and , respectively. Since these two events are mutually exclusive $\mathbf{p_r+q_r=1.0}$. This model assumes that once a subarea of agricultural land is hit by a dry spell, it remains under this state in the subsequent time instances. Therefore, as time passes, the number of dry spell hit subareas steadily increases until the whole region comes under the influence of drought. Such a regional model has been referred to as regional persistence model by Şen (1980b). Application of this model is convenient for agricultural droughts in arid and semi-arid regions where long drought periods exist.

The second model takes into account the regional as well as temporal occurrence probabilities of wet and dry spells. The probabilities of temporal SMC surplus $\mathbf{p_t}$ and SMC deficit $\mathbf{q_t}$ spell occurrences are mutually exclusive, and therefore, $\mathbf{p_t+q_t=1.0}$. In this model, in an already drought stricken area, subareas are subject to temporal drought effects in the next time interval. This model is also known as multi-seasonal model, because it can be applied for a duration which may include several dry and wet periods. Since, agriculture is a seasonal activity, this seasonal model is suitable for agricultural drought modeling. Although, Lee et al (1986) suggested a multi-year drought durations analysis, their arguments were based on several hazard- function models which were examined with regard to their ability to represent the duration-dependent termination rate of drought data set. The view taken in this chapter is entirely different and based on the objective probability models as spatio-temporal concepts.

Regional Drought Modeling

Let an agricultural land be divided into **m** mutually exclusive subareas each with the same spatial and temporal drought chance. The Bernoulli distribution theory can be employed to find the extend of drought area, $\mathbf{A_d}$, during a time interval, $\mathbf{\Delta t}$. The probability of $\mathbf{n_1}$ subareas stricken by drought can be written according to Bernoulli distribution as (Feller, 1967)

$$P_{\Delta t}(A_d = n_1) = \binom{m}{n_1} p_r^{n_1} q_r^{m-n_1} \qquad p_r+q_r=1.0 \quad (9)$$

This implies that out of **m** possible drought prone subareas, $\mathbf{n_1}$ have SMC deficit and hence the areal coverage of drought is equal to $\mathbf{n_1}$ or in percentages $\mathbf{n_1/m}$. For the subsequent time interval , there are $\mathbf{(m-n_1)}$ drought prone subareas. Assuming that the evolution of possible SMC deficit and SMC surplus spells along time axis is independent over mutually exclusive subareas, similar to the concept in equation (9) it is possible to write for the second time interval that

$$P_{2\Delta t}\left(A_d = n_2\right) = \sum_{n_1=0}^{n_2} \binom{m}{n_1}\binom{m-n_1}{n_2-n_1} p_r^{n_1} p_r^{n_2-n_1} q_r^{m-n_1} q_r^{m-n_2} \quad (10)$$

where $\mathbf{n_2}$ the total number of drought is affected subareas during the second time interval. By considering equation (9), his expression can be rewritten succinctly in the form of recurrence relationship as

$$P_{2\Delta t}\left(A_d = n_2\right) = \sum_{n_1=0}^{n_2} P_{\Delta t}\left(A_d = n_1\right) P\left(A_d = n_2 - n_1\right) \tag{11}$$

where $\mathbf{P(A_d=n_2-n_1)}$ is the probability of additional $\mathbf{(n_2-n_1)}$ subareas to be effected by SMC deficit during the second time interval out of remaining $\mathbf{(m-n_1)}$ potential subareas from the previous time interval. With the same logic, extension of equation (11) for any successive time interval, i, furnishes all the required drought-area probabilities as

$$P_{i\Delta t}\left(A_d = n_i\right) = \sum_{n_{i-1}=0}^{n_i} P_{(i-1)\Delta t}\left(A_d = n_{i-1}\right) P\left(A_d = n_i - n_{i-1}\right) \tag{12}$$

For **i**=1 this expression reduces to its simplest case which does not consider time variability of drought occurrences as presented by Şen(1980b) and experimentally on digital computers by Tase (1976). Furthermore, the probability of agricultural drought area to be equal to or less than a specific number of subareas **j** can be evaluated from equation (12) according to

$$P_{i\Delta t}\left(A_d \le j\right) = \sum_{k=0}^{j} P_{i\Delta t}\left(A_d = k\right) \tag{13}$$

The probability of having, $\mathbf{n_1'}$, SMC deficit subareas given that there are $\mathbf{n_1}$ SMC deficit subareas at the beginning of the same time interval within the whole region can be expressed as

$$P_{\Delta t}\left(A_d = n_1' \middle| A_d = n_1\right) = \binom{m}{n_1}\binom{n_1}{n_1 - n_1'} p_r^{n_1} p_t^{n_1 - n_1'} q_r^{m-n} q_t^{n_1'}$$

or shortly,

$$P_{\Delta t}\left(A_d = n_1' \middle| A_d = n_1\right) = P_{\Delta t}\left(A_d = n_1\right)\binom{n_1}{n_1 - n_1'} p_t^{n_1 - n_1'} q_t^{n_1'} \tag{14}$$

It should be noted that always $\mathbf{n_1 \ge n_1'}$ and the difference, $\mathbf{j=n_1-n_1'}$ gives the number of transitions. On the basis of equation (14), a general equation for the marginal probability of observing $\mathbf{n_1}$' SMC deficit spells at the end of the same time interval, after simple algebra, becomes

$$P_{\Delta t}\left(A_d = n_1'\right) = \sum_{k=0}^{m=n_i'} P_{i\Delta t}\left(A_d = k + n_i'\right)\binom{k = n_i'}{k} p_t^k q_t^{n_i'} \tag{15}$$

Hence, the regional agricultural drought occurrences during the second time interval follow similarly to this last expression, and generally, for the i-th step, it takes the following form

$$P_{i\Delta t}\left(A_d = n_i'\right) = \sum_{k=0}^{m=n_i'} P_{i\Delta t}\left(A_d = k + n_i'\right)\binom{k + n_i'}{k} p_t^k q_t^{n_i'} \tag{16}$$

Its validity has been verified using digital computers. The PDFs of areal agricultural droughts for this model are shown in Figure 5 with parameters $\mathbf{m=10,\ p_r=0.3,\ p_t=0.2}$ and i = 1,2,3,4 and 5. The probability functions exhibit almost symmetrical forms irrespective of time intervals although they have very small positive skewness.

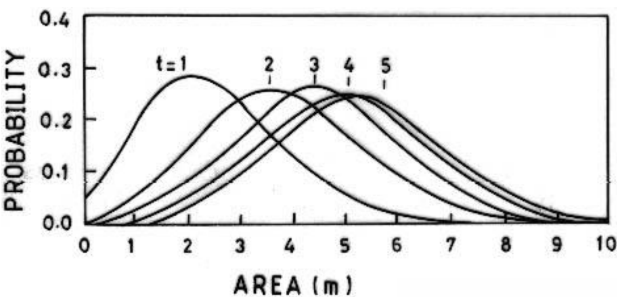


Figure 5. Probability of drought area for multi-seasonal model ***(m=10; p_r=0.3;p_t=0.2)***

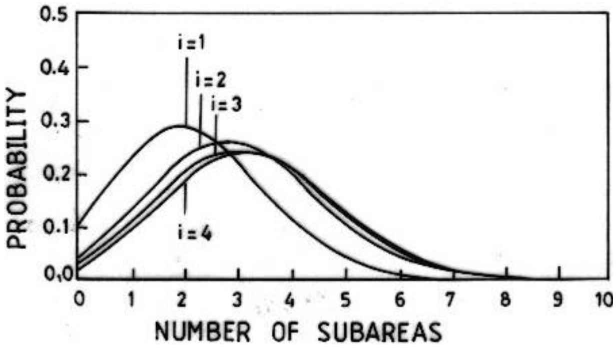


Figure 6. Drought area probability for multi-seasonal model ($m=10$; $p_r=0.3$; $p_t=0.5$).

Another version of the multi-seasonal model is interesting when the number of continuously SMC deficit subareas appear along the whole observation period. In such a case, the probability of drought area in the first time interval can be calculated from equation (9). At the end of the second time interval, the probability of **j** subareas with two successive SMC deficits given that already $\mathbf{n_1}$ subareas had SMC deficit in the previous interval can be expressed as:

$$P_{2\Delta t}\left(A_d = j \middle| A_d = n_1\right)=P_{\Delta t}\left(A_d = n_1\right)\binom{n_1}{j}p_t^j q_t^{n_1-j} \qquad (17)$$

This expression yields the probability of having subareas to have SMC deficit out of which j subareas are hit by two SMC deficits, i.e, there are subareas with one SMC deficit. Hence, the marginal probability of continuous SMC deficit subarea numbers is

$$P_{2\Delta t}\left(A_d = j\right)= \sum_{k=0}^{m-j} P_{\Delta t}\left(A_d = k+j\right)\binom{k+j}{j}p_t^j q_t^k$$

In general, for the i-th time interval it is possible to write

$$P_{i\Delta t}\left(A_d = j\right)= \sum_{k=0}^{m-j} P_{(i-1)\Delta t}\left(A_d = k+j\right)\binom{k+j}{j}p_t^j q_t^k \qquad (18)$$

The numerical solutions of this expression are presented in Figure 6 for $\mathbf{m=10}$, $\mathbf{p_r=0.3}$ **and** $\mathbf{p_t=0.5}$. The probability distribution function is positively skewed.

DROUGHT PARAMETERS

The global assessment of model performances can be achieved on the basis of drought parameters such as averages, i.e., expectations and variances, but for drought predictions, the PDF expressions as derived above are significant. The expected, i.e., average number of SMC deficits, $\mathbf{E_1(A_d)}$, over a region of **m** subareas during time interval, $\mathbf{i\Delta t}$ is defined as

$$E_i\left(A_d\right)= \sum_{k=0}^{m} kP_{i\Delta t}\left(A_d = k\right) \qquad (19)$$

Similarly, the variance, $\mathbf{V_i(A_d)}$, of drought affected area is given by definition as

$$V_i\left(A_d\right)= \sum_{k=0}^{m} k^2 P_{i\Delta t}\left(A_d = k\right)-E_i^2\left(A_d\right) \qquad (20)$$

The substitution of equation (12) into equation (19) leads to drought stricken average area within the whole region as

$$E_i\left(A_d\right)=mp_r \sum_{k=0}^{i-1} q_r^k \qquad (21)$$

or succinctly,

$$E_i\left(A_d\right)=m\left(1-q_r^i\right) \qquad (22)$$

Furthermore, the percentage of agricultural drought stricken area, PiA, can be calculated by dividing both sides by the total number of subareas, m, leading to

$$\mathbf{P^i_A = (1 - q_r^i)} \qquad (23)$$

Figure 7 shows the change of drought stricken area percentage with the number of SMC deficit subareas, **i**, for given SMC deficit probability, $\mathbf{q_r}$.

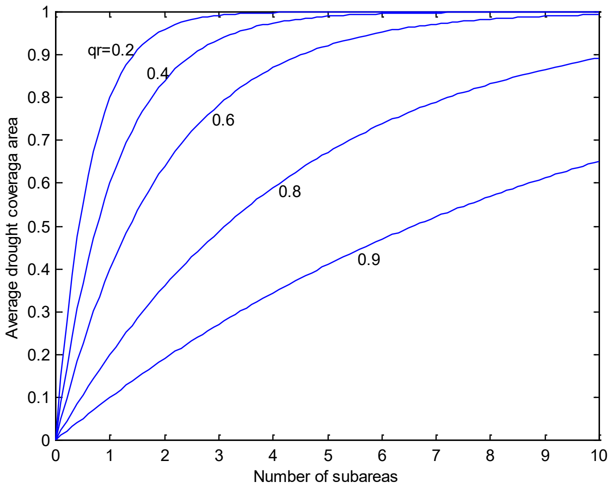


Figure 7. Drought percentage areal coverage

For regional drought variations in the first time interval (i=1), from equation (23), $\mathbf{P^1_A=p_r}$. On the other hand, for the whole area to be covered by drought theoretically $i\rightarrow\infty$ and therefore, $\mathbf{P^\infty_A=1}$. It is obvious that the temporal agricultural drought percentage for a region of **m** subareas at any time **i**, is $\mathbf{p_r \leq P^i_A} \leq 1$.

As the probability of SMC deficit spell in a region increases, the average drought area attains to its maximum value in relatively shorter time as can be written from equation (23)

$$\mathbf{i = Ln(1-P^i_A)/Ln(1-p_r)} \quad (24)$$

Hence, this expression provides the opportunity to estimate average time period that is required for a certain percentage of the region to be covered by drought. Figure 8 indicates the change of i with p_r, that is the SMC surplus probability.

Furthermore, in practical applications the probability of SMC can be approximated empirically as 1/m or preferably as 1/(m+1). The substitution of these conditions into equation (24) gives

$$\mathbf{i = Ln(1-P^i_A)/[Ln(m/(m+1)]} \quad (25)$$

This expression confirms that regional drought durations are affected mainly by its size rather than its shape as was claimed by Tase and Yevjevich (1978).

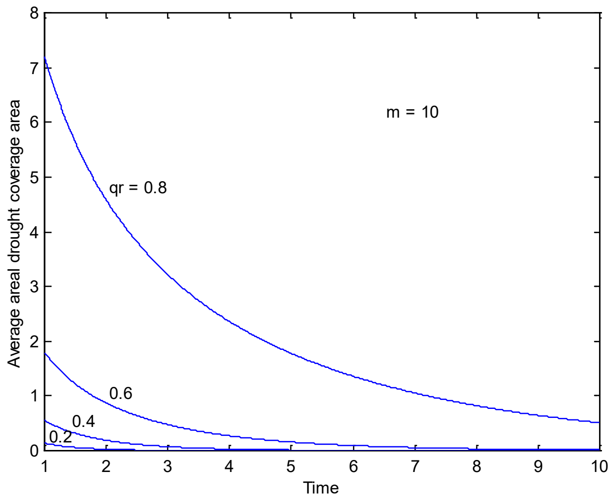


Figure 8. Drought time change by pr

The next significant regional drought parameter is the variance which is a measure of drought variability. In general, the smaller the variance the smaller the areal drought coverage percentage. The variance of the regional persistence model can be found from equations (9) and (12) after some algebra as

$$V_i(A_d) = m(1-q_r^t)q_r^t \quad (26)$$

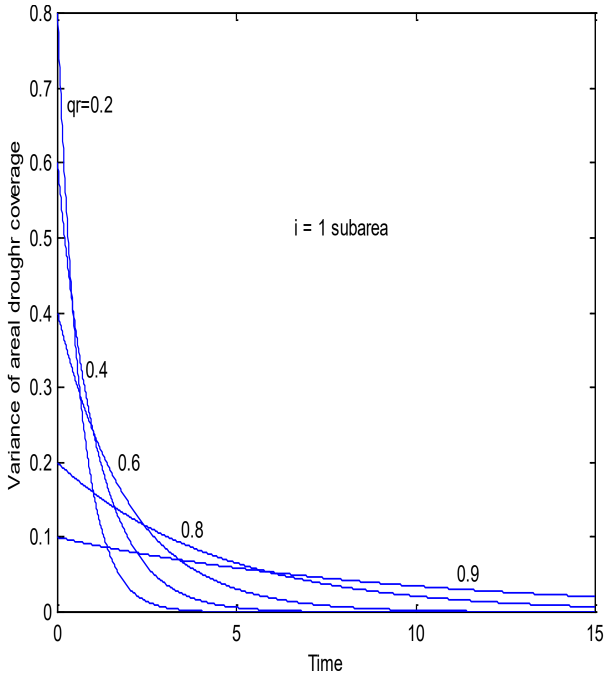
Similarly, it is better in practice to standardize this variance by dividing both sides by the total area, m, which gives percentage variance, PVi,T in the case of i subarea coverage after T time duration

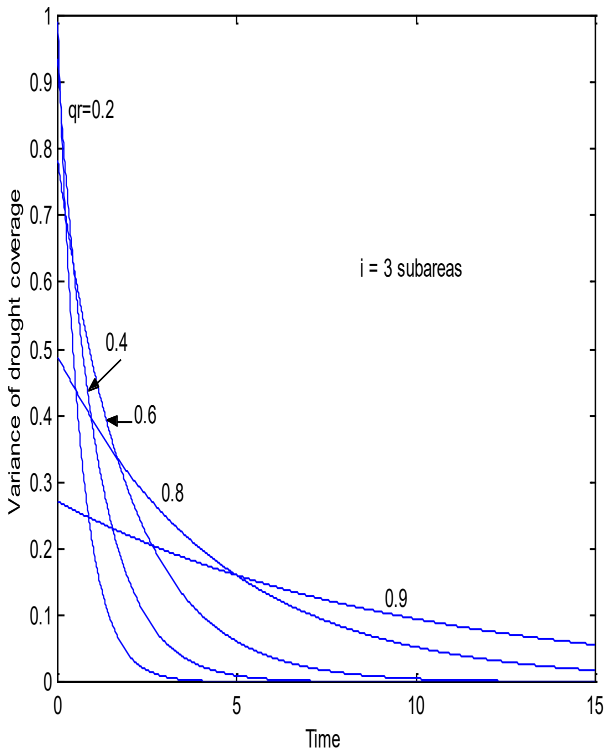
$$\mathbf{PV^{i,T} = (1-q_r^i)q_r^T} \quad (27)$$

Furthermore, consideration of equation (23) together with this last expression yields the relationship between percentages of average and variance drought coverages as

$$\mathbf{PV^{i,T} = PA^i q_r^T} \quad (28)$$

Figure 9 shows the change of regional drought variance percentage with i SMC deficit affected number of subareas at different times for a given SMC deficit probability, q_r=0.7.





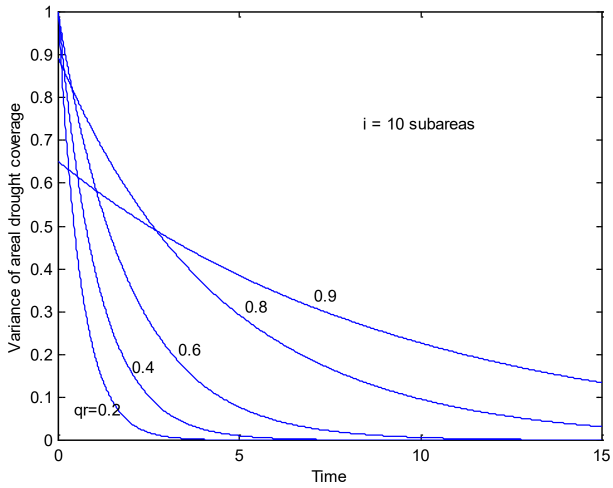


Figure 9. Areal drought variance percentage variation.

Another application of spatio-temporal agricultural drought occurrence is possible by considering both spatial SMC deficit probability, q_r and temporal SMC surplus probability, p_t. It is rather cumbersome to find a concise expression for the expectation of this case at all times. However, for the first time interval :

$$\mathbf{E_1(A_d) = m(1\text{-}q_r)(1\text{-}p_t)} \qquad (29)$$

which exposes explicitly the contribution of the regional and temporal dry spell effects on the average areal drought. Figure 10 shown drought spatial and temporal average variations for given SMC probabilities.

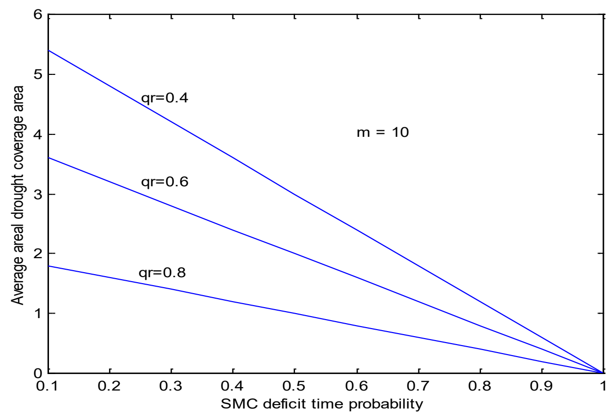


Figure 10. Average areal drought coverage by considering spatio-temporal variations during the first time interval

Finally, the variance of the drought area coverage by simple spatio-temporal model considerations, it is possible to derive for the first time interval that

$$\mathbf{V_1(A_d) = E_1(A_d)(q_r+p_t\,p_r)} \qquad (30)$$

The numerical solution of this expression is given for various combinations of pr and pt in Figure 11.

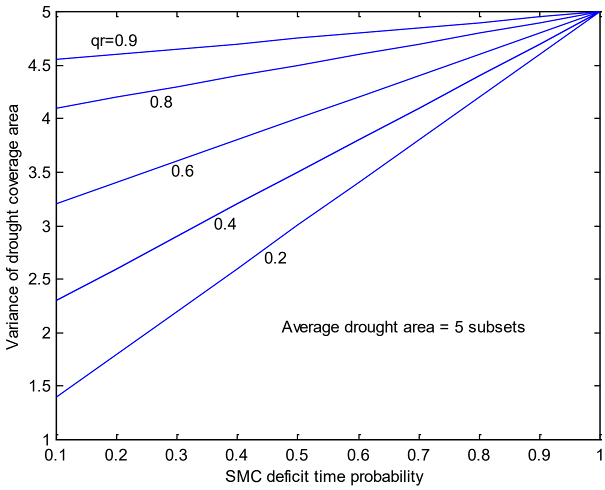


Figure 11. Average variance of drought area for various basic probability values

CONCLUSIONS

The probability distribution functions of regional and temporal agricultural droughts are derived for independent dry and wet spell occurrences of soil moisture content (SMC). Two basically different probabilistic models are proposed for regional drought modeling. Regional drought parameter variations are assessed graphically. The following conclusions are valid for regional and temporal drought occurrences :

(i) drought occurrences are dependent on the regional and temporal SMC dry and wet spell probabilities as well as size of the region considered.

(ii) drought area distribution within a region without considering temporal probabilities becomes negatively skewed as its size increases. Initially, it can be approximated by a normal distribution. For multi-seasonal model the same distribution has an approximate normal distribution provided that continuous drought duration is not considered. Otherwise, it is positively skewed.

(iii) drought probabilities over a region are more affected by its size.

REFERENCES

Bokan, V.K., Cracknell, A.P., and Heathcote, R.L. (2005). Monitoring and Predicting Agricultural Drought. A Global Study. Oxford University Press, 472 pp.

Dando, W.A., 1980. The geography of famine. London, Edward Arnold.

Downer, R., Siddiqui, M.M. and Yevjevich, V. (19667). Applications of runs to hydrologic droughts. Colo. State Univ., Fort Collins, Colo., Hydrol. Pap. 23.

Dracup, A.J., Lee, K.S. and Paulson, E.G. (1980). On the statistical characteristics of drought events. Water Resour. Res., Vol. 16, No.2, 289-196.

Feller, W., 1967. An Introduction to Probability Theory and its Application. John Wiley and Sons., New York, 509 pp.

Glieck, P.H., 1993. Water in Crisis. A guide to the world's Fresh Water Resources. Oxford University Press, 473 pp.

Guerrero-Salazar, P.L.A. (1973). Statistical modeling of droughts. Ph. D. Dissertation, Colo. State Univ., Fort Collins, Colo., (unpublished).

Guerrero-Salazar, P.L.A. and Yevjevich, V. (1975). Analysis of drought characteristics by the theory of runs. Colo. State Univ., Fort Collins, Colo., Hydrol. Pap., 80.

Gumbel, E.J. (1963). Statistical forecast of droughts. Bull. Int. Assoc. Sci. Hydrol., Vol. 8, No.1, 5-23.

Horn, D. (1989). Characteristics and spatial variability of droughts in Idaho. ASCE, Jour. Irrig. and Drain. Engrg., Vol.115, No.1, 111-124.

Hsiao, T.C., 1992. Plant-atmosphere interactions, evapotranspiration, and irrigation scheduling. Int. Centre for Advanced Mediterranean Agriculture Studies, Bari, 15-16.

Kates, R.W. and Kasperson, J.X., 1983. Comparative risk analysis of technological hazards. (a review). Proc. Nat. Aca. Sci. USA 80: 7027-38.

Karamouz, M., Torabi, S., and Araghinejad, S., 2004. Analysis of Hydrologic and Agricultural Droughts in Central Part of Iran. ASCE, Jour. Hydrologic Engrg., Vol.9, No. 5, 402-414.

Lee, K.S., Sadeghipour, J. and Dramp, J.A. (1986). An approach for frequency analysis of multi-year drought durations. Water Resour. Res., Vol.22, No.5, 655-662.

Llamas, J. Siddiqui, M.M. (1969). Runs of precipitation series. Colo. State Univ., Fort Collins, Colo., Hydrol. Pap., 33.

Millan, J. Yevjevich, V. (1971). Probabilities of observed droughts. Colo. State Univ., Fort Collins, Colo., Hydrol. Pap., 50.

Millan, J. (1973). Statistical properties of runs as applied to hydrologic droughts. Floods and Droughts. Water Resources Publications, 627-636.

Saldarriaga, J. and Yevjevich, V. (1970). Application of run-lengths to hydrologic time series. Colo. State Univ., Fort Collins, Colo., Hydrol. Pap., 40.

Smith, K. (1965). Principles of Applied Climatology. McGraw-Hill Book Co., London, 233 pp.

Şaylan, L. (2000). The effect of the environmental factors on the evapotranspiration in different growth phases of soybean. Die Bodenkultur, No. 2, Vol. 51, 127-134.

Şaylan, L., Sönmez, F.K., and Eitzinger, J., 1994. Bitki iklim modelleri tarımsal kuraklığın analizine bir çözüm olabilir mi?. Is it possible to have a solution in plant-climate modeling of agricultural drought analysis? First National Hydrometeorology Symposium, 72-81.

Şen, Z. (1976). Wet and dry periods of annual flow series. Jour. Hydraul. Div., ASCE, Proc. Pap. 12497, Vol.102, No.HY10, 1503-1514.

Şen, Z. (1977). Run-sums of annual flow series. Jour. Hydrol., Vol.35, 311-324.

Şen, Z. (1980a). Statistical analysis of hydrologic critical droughts. Jour. Hydraul. Div., ASCE, Proc. Pap. 14 134, Vol.106, No.HY1, 99-115.

Şen, Z. (1980b). Regional drought and flood frequency analysis : Theoretical considerations. Jour. Hydrol., Vol.46, 265-279.

Şen, Z. (1989). The theory of runs with applications to drought prediction - Comment. Jour. Hydrol., Vol.

Şen, Z. (1990). Critical drought analysis by second order Markov chain. Jour. Hydrol., Vol.

Şen, Z., and Boken, V. K. (2005). Techniques to predict agricultural droughts. Oxford University Press, 40-54.

Smith, K., 2001. Environmental Hazards. Assessing Risk and Reducing Disaster.

Routledge, New York, 392 pp.

Tase, N. (1976). Area-deficit-intensity characteristics of droughts. Colo. State Univ., Fort Collins, Colo., Hydrol. Pap. 87.

Tase, N. and Yevjevich, Y. (1978). Effects of size and shape of a region on drought coverage. Hydrological Sciences Bulletin, Vol.23, No.2, 203-213.

Yevjevich, V., 1967. An objective approach to definitions and investigations of continental hydrologic drought. Hydrology Paper No. 23, Colorado State University, Fort Collins, Co.

Wilhite, D.A., and Glantz, M.H., 1985. Understanding of drought phenomenon: The role and definition. In Water International, 10, 111-120.

Wilhite, D. A., 1996. A Methodology for Drought Preparedness. Natural Hazards, 13, 229-252.

Wolkewits, H. and Stenitzer, E., 1976. Der Saltztransport in mit Wasser ungesaettigen Boden, Abschlussbericht WO 121/24, Deutsche Forschungsgemeinschaft, Bonn-Bad Godesberg.

SU VAKFI KURAKLIK KÜLLİYESİNDE DAHA ÖNCE YAYINLANAN BÜLTENLER

SAYI 3 2017 Şubat (February) TÜRKÇE	Kuraklık ve Susuzluk *Zekâi Şen*
SAYI 2 2017 Ocak (January) TÜRKÇE	İklim Değişikliği ve Kuraklık *Zekâi Şen*
SAYI 1 2016 Aralık (December) TÜRKÇE	Kuraklık Göstergeleri *Zekâi Şen*

Tüm Su Vakfı bültenlerini http://bulten.suvakfi.org.tr adresinden bilgisayarınıza indirebilirsiniz.

SU VAKFI

Libadiye Cad. Doğanay Sokak No:6 Kat:4 Üsküdar İstanbul
Tel: (216) 412 3383 - Faks: (216) 412 3390
suvakfi@suvakfi.org.tr - www.suvakfi.org.tr