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Examining the probable length in days of wet and dry spells in Khuzestan province

Seyed Hossein Mirmousavi

University of Zanjan, Faculty of Humanities,
University Blvd.,45371-38791, Iran
hossein.mousavi047@gmail.com

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Abstract—This study evaluated the probable length in days of dry and wet spells in Khuzestan province using daily rainfall data from 11 synoptic stations during the period 1990–2012. Transfer matrix calculations and model tests were performed using Matlab software. For interpolation maps, kriging in ARC GIS 10.2 software was used. Results indicated that the probability of dry days occurring in Khuzestan province increases from the south to the north. The highest probabilities of a two-day dry spell were 15% in the north and 12% in the northeast of the province. The probability of a 3-day dry spell in the north and northeast was 10%. Moving to the south and southwest of the province, the probability decreases, amounting to 6% in the southwest. Results of calculations of return periods of wet and dry days showed the probability of the dry-days return period increases from the north to the south. An investigation of the role of general circulation in the creation of wet and dry periods showed that 4 patterns are effective in their production.

Key-words: Markov chain, probability, dry and wet spells, Khuzestan Province.

1. Introduction

Wet spells and dry spells are two main physical characteristics of rainfall occurrence, and the volume of rainfall in a geographical area depends heavily on the distribution of such spells. It is, therefore, important to investigate the occurrence patterns of wet and dry spells scientifically through model-based analysis, that consists of studying the statistical properties of two common indicators, the spell length and spell frequency. Such studies are essential for agricultural planning, water resource management, and other interests such as fisheries, health, ecology, environment, etc. Several kinds of stochastic models have been used to describe frequency distributions of spell lengths at spatial and temporal levels. The fitted probability distributions of spell lengths under the models are used to study the persistence properties of wet and dry spells. Since spell lengths govern the persistence properties of the daily precipitation process, it is desirable to use a criterion to select the best model from among a series of competitive models that is fitted successfully to the observed datasets.

In order to put our discussion into the proper perspective, we related our work to the existing literature. The model most frequently used to generate consecutive series of dry and wet days is the first-order, two-state, homogeneous Markov chain that has been applied by and is very popular among various researchers, *Todorovic* and *Woolhiser* (1974), *Berger* and *Goossens* (1983), *El_seed* (1987), *Haggstrom* (2002), *Bekele* (2002), *Anagnostopoulou et al.* (2003), *Alasseur et al.* (2004), *Ana* and *Paulo* (2007), *Asakereh* (2009), *Fischer et al*. (2013)). An essential improvement to the reproduction of short and long spells was made by *Berger* and *Goossens* (1983) and *Nobilis* (1986) using the higher order Markov chain and Eggenberger-Polya distribution. They found that short spells were best fitted by the fourth order Markov chain, whereas the Eggenberger-Polya distribution gave the best fit to the long series. *Deni* and *Jemain* (2008) proposed a model constituting two different geometric distributions. In the referred study, both geometric distributions were separated according to the length of dry spells. Results of the works suggested that mixed distribution, including the geometric one, could be promising in reproducing long dry periods. For wet spells, it was also observed that simple geometric distribution could be promising. Recently, following the idea of *Deca et al*. (2010), a mixture distribution based on a weighted sum of two geometric distributions, as well as that of one geometric and one Poisson distribution, was applied by *Mathugama* and *Peiris* (2011). The first model exhibits a good fit for dry spells, and the latter can be employed for wet periods. More recently, *Ababaei et al*. (2012) found that both the Markov chain of order two and negative binomial distribution can be used to estimate wet spells in Qazvin (Iran).

Khuzestan province is one of the most important agricultural areas in Iran. Due to successive droughts, farmers in this province have endured many losses. In this region, the incidence of consecutive dry days is a main factor in increasing the amount of damage to the agricultural sector (*Nadi et al*., 2012). For this reason, it is necessary to carefully examine the consecutive dry days in the area. The present study examined in detail the ability of the Markov models to analyze the wet or dry condition of a given day in this area.

2. Data

In this study, daily rainfall data was collected from 11 meteorology stations. The period 1990–2012 was chosen for the evaluation of the model. A wet day was defined as a 24-hour period with total rainfall exceeding 0.1 mm, and a dry day was defined as one with measurable precipitation <0.1 mm. The pressure data used were the NMC grid data in different windows over Europe and Middle East at the grid resolution 2.5°×2.5°. Several geopotential heights (500 hPa and sea level pressure (SLP)) were used. The selected area experienced a large part of the systems affecting Iran during the years (from 1970 to 2013) involved. This region is located within 20–60° N and 20–80° E. Data used from the NCEP site (www.ncep.noaa.gov) is provided.

3. *Method*

3.1. Markov chains

A Markov chain can be defined as a type of time-ordered probabilistic process that goes from one state to another according to the probabilistic transition rules that are determined by the current state only (*Haggstrom*, 2002). That is, the probability of a day being in a certain state (either wet or dry) is conditioned on the states of the previous periods, where the number of previous periods is termed as the order of the chain.

In the first-order, two-state Markov model, the current state is dependent solely upon the state of the previous period, while in the second–order, two-state Markov chains, the current state is determined by the states of the two previous periods (*Hakimi-Pour*, 1998).

When recording whether a measurable amount of rain has occurred over time at a particular location (2-state time series), data is in the form of a discrete state series. The most commonly used model for discrete state series is a low-order stationary Markov chain. Such models are used to predict the occurrence of certain sequences.

The states of the system are dry and wet. A wet state is defined as a 24-hour period measured from 8:30 a.m. with total rainfall exceeding some threshold amount (0.1 mm). Otherwise, the state is taken as dry (*Zarei* and *Shahkar*, 2002). The discrete state series of rainfall can be represented as $X_1, X_2, X_3, \ldots\ldots, X_t$ for a t length sequence, where:

$$X_t = 0, \text{ if day } t \text{ is dry,}$$

$$X_t = 1, \text{ if day } t \text{ is wet.} \qquad (1)$$

3.2. First-order Markov model

The probabilities of a first-order Markov chain are defined as:

$$P\ \{X_t = j \mid X_{t-1} = i\}\ i,j = 0,1\ . \tag{2}$$

The *transition probability* P_{ij}, (where $i, j = 0, 1$) is the probability that if the system is in state i at any observation, it will be in state j at the next observation. As probabilities, the numbers P_{ij} must all lie in the interval [0, 1]. Transitional probabilities for the first order can be expressed as follows:

$$Pij(t) = P\{\ X_t = j \mid X_{t-1} = i\ \}\ i,j = 0,1\ . \tag{3}$$

For any fixed i, $\{i = 0, 1\}$, we must have $P_{i0} + P_{i1} = 1$.

This expresses the fact that if the system is in one of the states at one observation, it will with certainty be in one of the two states at the next observation. With these transition probabilities, a 2×2 matrix $\mathbf{P} = \{P_{ij}\}^{T}$, called the transition matrix of the Markov process, can be formed where the sum of the entries in each column of **P** is one.

$$\mathbf{P} = \begin{pmatrix} p_{00} & p_{10} \\ p_{01} & p_{11} \end{pmatrix}. \tag{4}$$

The probability vectors $\boldsymbol{p}^{(n)}$ for $\boldsymbol{n} = 0, 1, 2, \ldots\ldots$ are said to be the state vectors of a Markov process, where $pi^{(n)}$ is the probability that the system is in the ith state at the nth observation. In particular, the state vector $\boldsymbol{p}^{(0)}$ is called the initial probability or initial state vector of the Markov process. If **P** is the transition matrix and $\boldsymbol{p}^{(n)}$ is the state vector at the nth observation, one can write:

$$\mathbf{P}^{(n+1)} = \boldsymbol{p}^{(n)}\mathbf{P} \tag{5}$$

Where $\boldsymbol{p}^{(n+1)}$ is the state vector at the $n+1$th observation. From this it follows that:

$$\mathbf{P}^{(n)} = \boldsymbol{p}^{(0)}\mathbf{P}^{n} \tag{6}$$

i.e., the initial state vector $\boldsymbol{p}^{(0)}$ and the transition matrix **P** determine the state vector $\boldsymbol{p}^{(n)}$ at the nth day. The nth step transition probabilities are called conditional probabilities and is denoted by $P_{ij}^{(n)}$, (where $i, j = 0, 1$) with $\mathbf{P}_{ij}^{(n)} \geq 0$, for n=0,1,2,3…., and:

$$\sum_{j=0}^{1} p_{ij}^{(n)} = 1 \ . \tag{7}$$

$\mathbf{P}^{(n)} = \boldsymbol{p}^{(0)}\mathbf{P}$ in matrix notation for the 1th order Markov chain can be written as (*Chynlar*, 2002):

$$\left(p_0^{(n)} p_1^{(n)}\right) = \left(p_0^{(0)} p_1^{(0)}\right) \begin{pmatrix} p_{00} & p_{10} \\ p_{01} & p_{11} \end{pmatrix} n \ . \tag{8}$$

Moreover, the calculation for the continuation of wet and dry days uses the following equation (*Berger* and *Goossens,* 1983):

$$P_m = \boldsymbol{p}^{m-1}\boldsymbol{q} \tag{9}$$

Return periods of dry and wet days, with the continuity of m-day, is calculated using the following equation:

$$T_m = \frac{1}{\boldsymbol{p}^{m-1}\boldsymbol{q}} \tag{10}$$

One of the main assumptions in Markov chains is stationarity. That is $P_{ij}(t)=P_{ij}$ for $t_k < t < t_{k+T}$ where T is the time interval taken to calculate the transitional probabilities. This assumes that the chance of rain remains constant within *T* day periods. The data was grouped into 2-day, 3-day, and 5-day groups and studied separately.

To evaluate the strength of the relationship between the occurrence of circulation patterns and rainfall, an index, called performance index (*PI*), is defined to measure the relative contribution of a particular pattern to the total rainfall amount. Specifically, the mean daily rainfall within cluster *i* is compared with the climatological mean daily rainfall, that is, (*Zhang*, 1995):

$$PI(i) = \frac{R_{i/n_i}}{R/n}, \tag{11}$$

where n_i is the number of days with pattern *i*; R_i is the total rainfall during those days; *R* is the total rainfall received during the study period, and n is the number of days in the study period. If *PI* is less than 1 in rainy weather, the pattern has no effect, and the placement of the pattern in the atmosphere of an area can be consecutive dry. If *PI* index is more than 1, consecutive wet days in the region will be created.

In order to assess the impact of dry periods on water resources and agricultural yield, linear regression and polynomial regression methods with the following equations were used:

$$\mu_{y|x} = \beta_0 + \beta_1 X \ . \qquad (12)$$

$$Y = \beta_0 + \beta_1 X + \beta_2 X^2 + \ldots + \beta_{p-1} X^{p-1} + \varepsilon \ . \qquad (13)$$

4. Study area

The province of Khuzestan, which occupies an area of 63,213 km^2 in southwestern Iran, is located between 48°E and 49.5°E longitudes and between 31°N and 32°N latitudes (*Fig. 1*). Topographic elevations in the province vary between 0 and 3740 m. The climate of the study area varies from arid to humid. The northern parts of the province experience cold weather, whereas the southern parts experience tropical weather. Summer is from April to September, whereas winter is from October to March. Annual mean of maximum summer temperatures in the province is about 50 °C (in July) and minimum winter temperature is 9 °C (in March). The annual amounts of rainfall are 165–200 mm in the southwest and 433–480 mm in the northeast, and about 70% of annual rainfall events occur from February to April (*Fig. 2*). The annual evaporation is 1500–2800 mm.

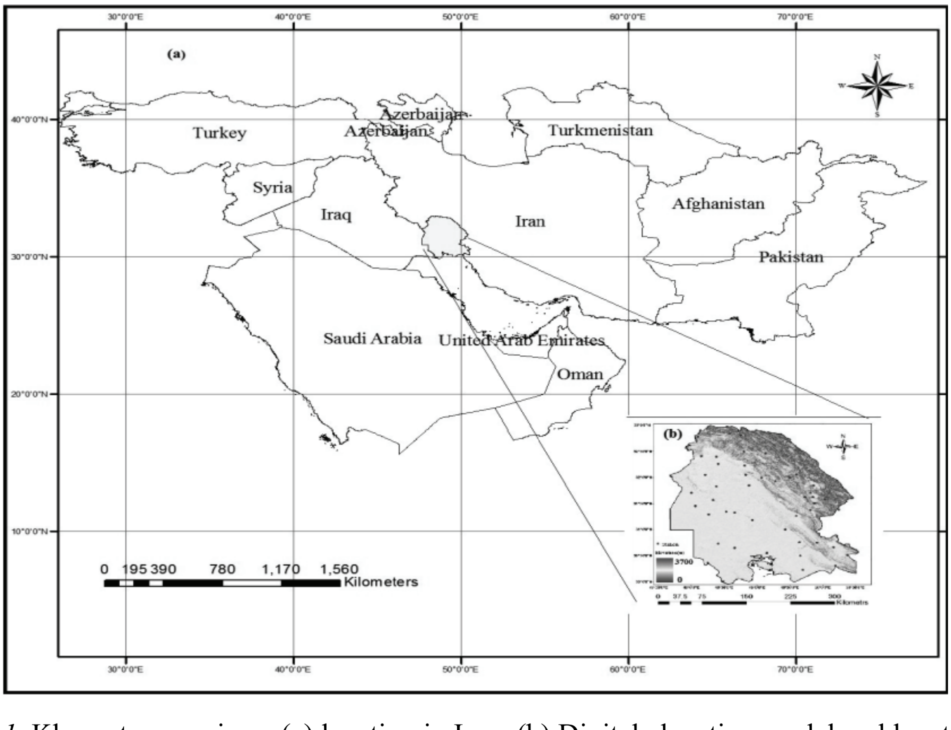

Fig. 1. Khuzestan province: (a) location in Iran; (b) Digital elevation model and locations of the studied stations.

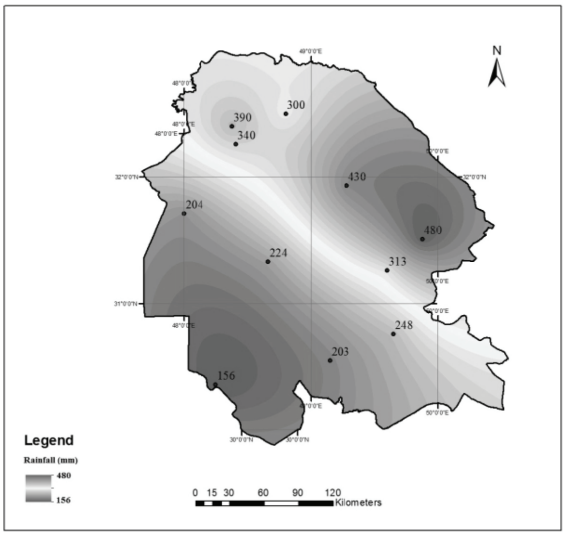

Fig. 2. Average annual rainfall in the Khuzestan Province.

5. *Results*

The calculation results showed that in Khuzestan province from the south to the north, the probability of dry days decreases. Maximum probability of dry days is found in the central and southwestern parts of the province (92%). This means that, on average, in the southwest part of the study area, 336 days per year are dry. The minimum probability of dry days was found in the northern region (74%). This means that in northern Khuzestan, on average, the probable number of dry days per year is 270. Overall, the average probability of dry days in Khuzestan province was 86%(*Fig. 3*).

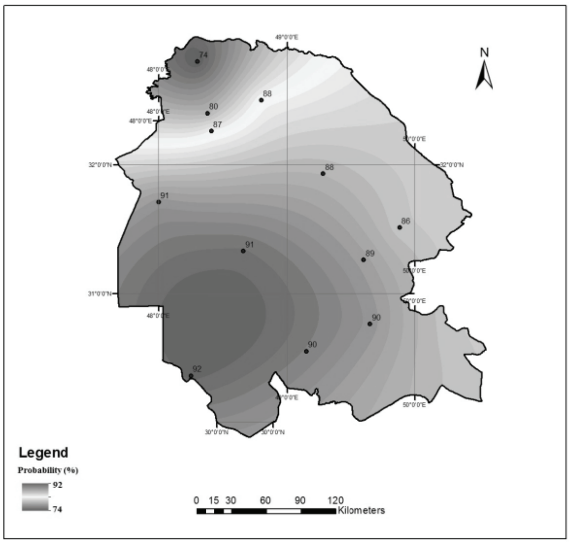

Fig. 3. Map of the dry day's probability (%).

An examination of the probability of a 2-day dry spell showed higher probabilities in the north (15%) and northeast (12%) than elsewhere in the study area. In the south and southwest, the probability of a 2-day dry spell is reduced so that in the southwest of the province, this rate reached the minimum amount of 6% (*Fig. 4*). Assessments showed that the probability for a 3-day dry spell in the north and northeast of the study area is approximately 10% and in the southwest of the province, the probability is equal to 6% (*Fig. 5*). Also, the probability of a dry spell lasting five days is less than that for a 3-day dry spell, so that the maximum value is in the northeast province (7%) and the minimum value is in the southern region at almost 2% (*Fig. 6*).

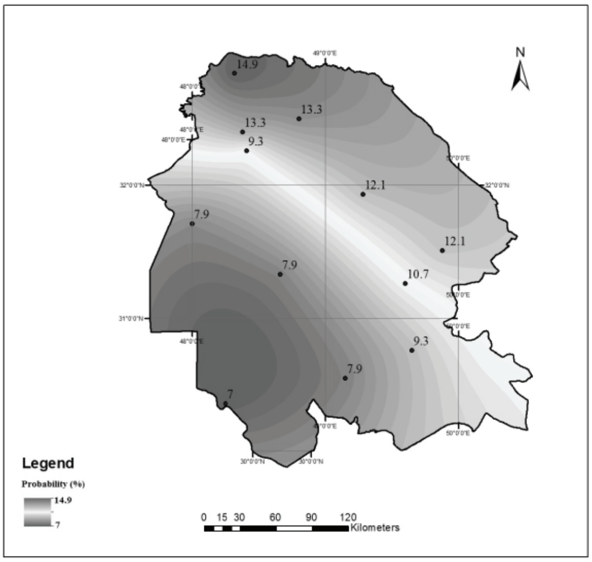

Fig. 4. Map probability of two days dry spell lengths (%).

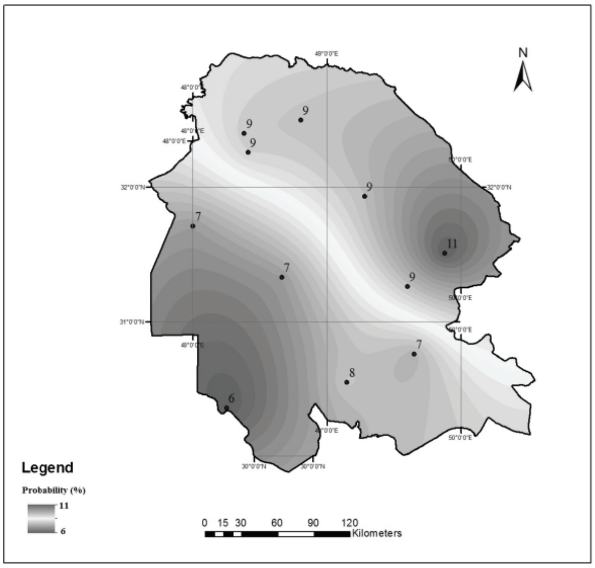

Fig. 5. Map probability of three days dry spell lengths (%).

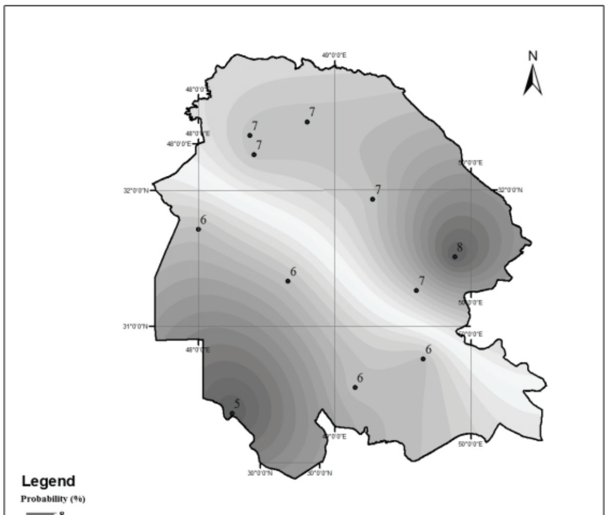

Fig. 6. Map probability of five days dry spell lengths (%).

5.1. Return period of 2-5-day dry spell

Calculating return periods of 2- to 5-day dry spells showed that the minimum length of a dry spell is 2 days, which occurred in the north and northeastern parts of Khuzestan province. This means that the probability of a dry spell lasting two days is higher in the north and northeast than in the south and southwest. Accordingly, the probable return period of a 2-day dry spell in the southwest of the province is, on average, 15 days, while in the north, the return period occurs once every 7 days. Studies have shown that most 2-day dry spells occur in the southwest of the province (*Fig. 7*).

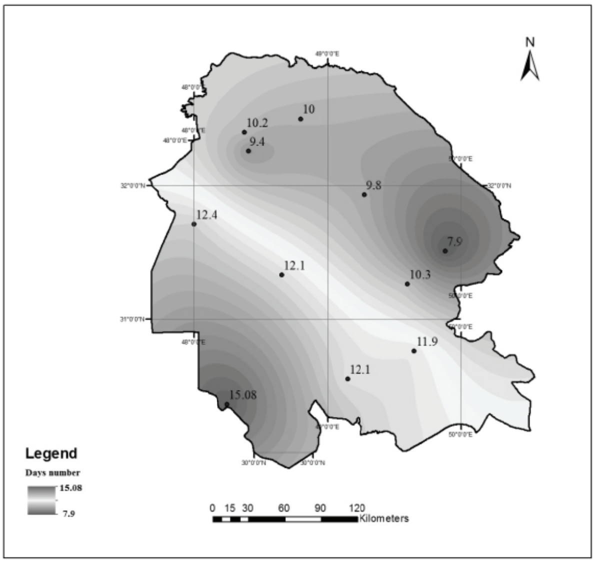

Fig. 7. Map of the persistence of a 2-day dry spell return period.

When the length of a dry spell increases to 3–5 days, the return period also increases; however, this data at the provincial level becomes a little slower. Evaluations showed that in the north and northeast of the province, the potential return period of the 3-day dry spell is once every 10 days, and the probability in the southwest province is once every 16 days (*Fig. 8*). The probability of the return period of a 5-day dry spell is much like that of a 3-day period. Every 17.5 days in the southern part of Khuzestan province and every 12.8 days in the northeast, the return period of a 5-day dry spell occurs (*Fig. 9*).

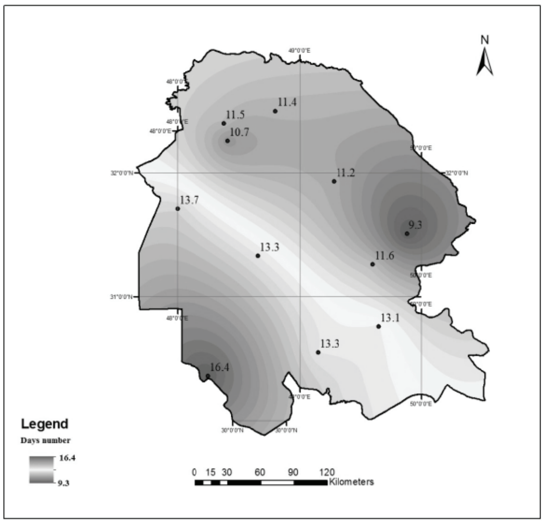

Fig. 8. Map of the persistence of a 3-day dry spell return period.

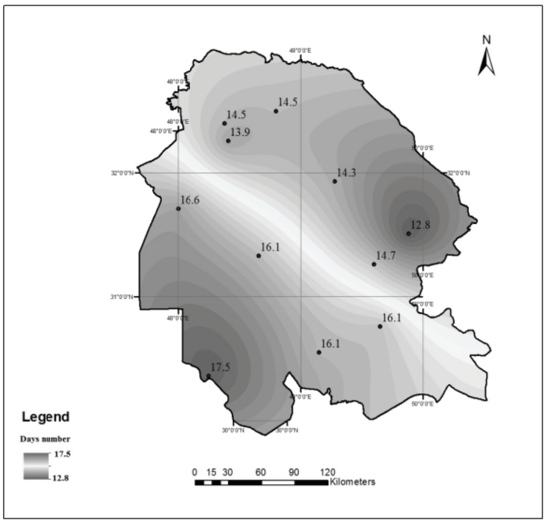

Fig. 9. Map of the persistence of a 5-day dry spell return period.

5.2. Assessment of the relationship between the height and distribution of dry and wet spell lengths in days

In order to assess the relationship between the height and distribution of consecutive dry days, simple linear regression was used. For this purpose, the elevation map of Khuzestan province was extracted using a 30-meter resolution satellite image (DEM) (*Fig. 10*). Then, using the Euclidean distance equation, 1200 elevation points were selected in Khuzestan province. Then, using kriging interpolation, the probabilities of lengths of dry spells in days for the 1200 selected points were extracted. The following regression equation was used to calculate the correlation ratio between the elevation and dry spell length in days:

$$y = 1E\text{-}07x^4 - 0.0001x^3 + 0.046x^2 - 7.146x + 377.88(12)\ , \qquad (14)$$

$$R^2 = 0.8394\ .$$

The results of the relation between the height and precipitation showed that, at a 99% confidence level, there is a strong correlation between these parameters. Based on this equation, correlation maps were drawn between elevation and dry spell lengths in days (*Fig. 11*). Exploration of this map indicated that the probability of dry days from the north to the south of the province is reduced. For wet spell lengths this situation is quite the contrary.

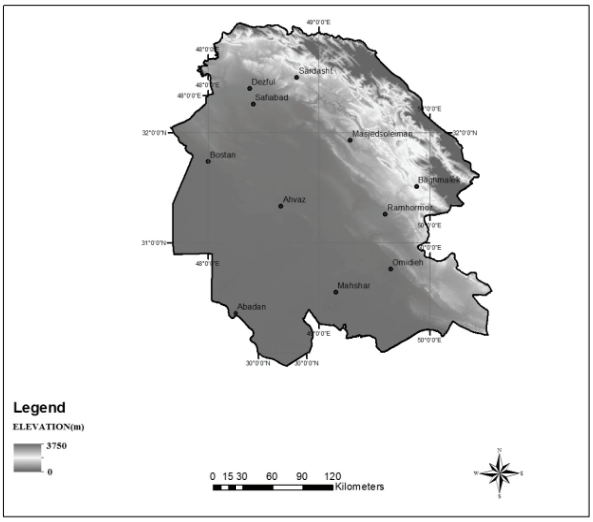

Fig 10. Elevation map of Khuzestan Province.

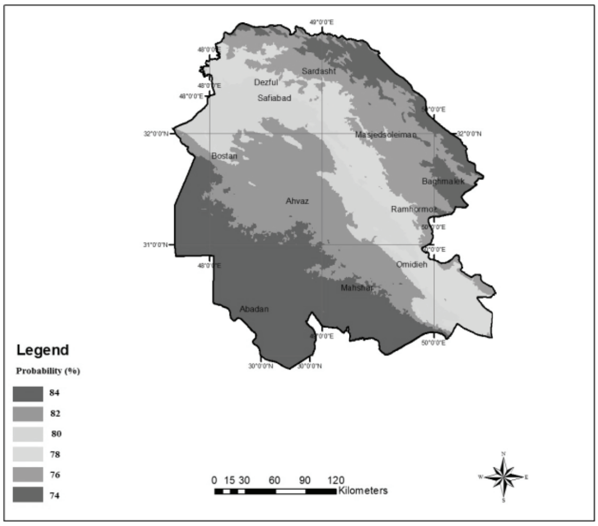

Fig. 11. Map of the relationship between the elevation and the length of dry spell.

5.3. Assessment of the relationship between the atmospheric circulation system and the probability of lengths of dry and wet spells in days

In order to assess the relationship between the atmospheric circulation patterns and the precipitation, the PI index was calculated and analyzed for 11 weather stations in the study area. This index specifies the conditional probability of rainfall in a circulation pattern. Results of PI, the role of each of the atmospheric circulation pattern showed the creation or lack of precipitation.

The results showed significant differences in the arrangement patterns of geopotential height of 500 hPa, sea level pressure, and circulation patterns in Iran. Analysis of atmospheric circulation systems showed three distinct patterns of rainfall in Iran.

5.4. Atmospheric circulation patterns for wet spell lengths

5.4.1. Pattern 1 (p1)

In Pattern 1, the 500 hPa geopotential height maps show a trough from northeastern Europe, to the southwest of Iraq. Because of the trough in the east, there is positive relative vorticity in this situation. Where there is sufficient moisture in the area, there is a chance of rain in this circulation pattern (*Fig. 12*-p1-A).

The map of the mean sea level pressure, the pressure of 1024 hPa, show deployment over Siberia. The pressure tabs stretch from the east-west to northwestern Europe. The low pressure from Saudi Arabia and North Africa in the mid-latitudes extends to the East Mediterranean region. The results of the PI index indicated that this pattern has the greatest impact on the southwestern and western regions of Iran (Khuzestan province). The present pattern causes precipitation and wet events in much of the country (*Fig. 12*-p1-B and C).

5.4.2. Pattern 2 (p2)

The composite map of 500 hpa geopotential height indicated the presence of a trough over Russia that expands to the Mediterranean along the southwest (*Fig. 12*-p2-A). The trough from the southwest (Khuzestan province) entered Iran and caused a lot of rain in these areas. The PI in Khuzestan is relatively high (PI = 3), which indicates that this pattern causes wet periods (*Fig. 12*-p2-B and C).

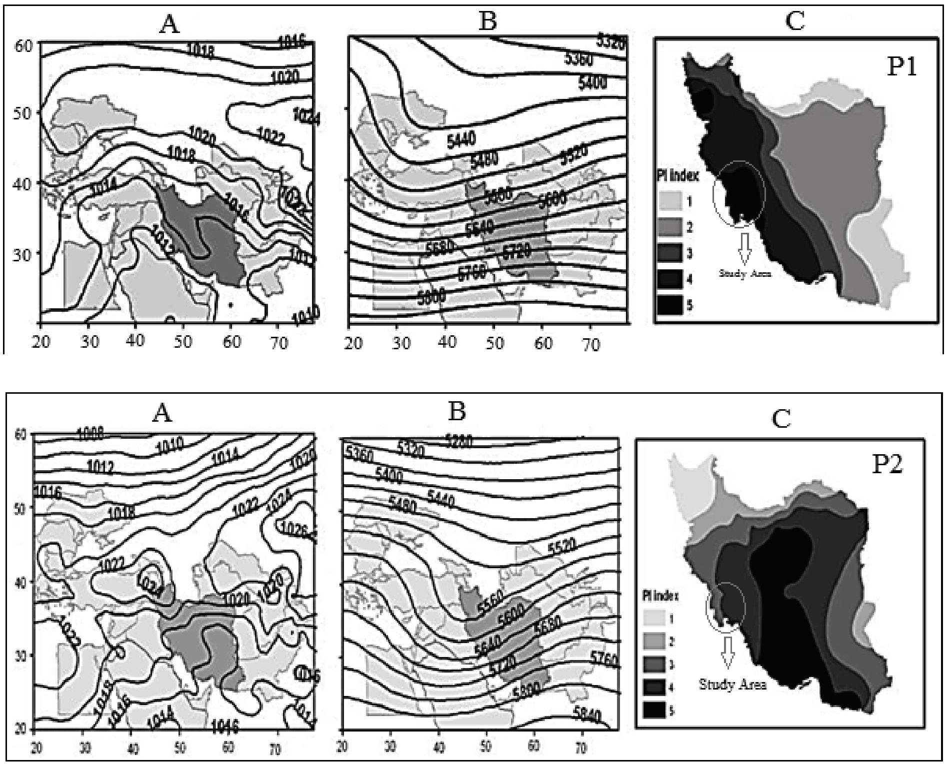

Fig. 12. Patterns of atmospheric circulation in Iran's Khuzestan province. A: 500 hPa mean geopotential height pattern ; B: mean sea level pressure pattern ;C: PI index pattern.

5.5. Atmospheric circulation patterns for dry spell lengths

5.5.1. Pattern 1 (p1)

The map of 500 hPa level showed a trough with a north-south direction expanding from the north of the Black Sea to the Red Sea. The eastern part of the trough has affected the northern regions of Iran (*Fig. 13*-p1-A). In this pattern, high pressure (with a center of 1026 hPa) was seen over Siberia and Europe, and the 1020 hPa isobaric curves expanded on the Mediterranean, North Africa, and the southeast. Formation of this synoptic pattern caused drought in most parts of Iran (*Fig. 13*-p1-B). The PI Index calculation also shows that with the exception of the northwestern areas, the index rate is less than 1 in other parts of the country. This means that the implementation of this pattern in the study area causes dry conditions (*Fig. 13*-p1-C).

5.5.2. Pattern 2 (p2)

In this pattern, a trough over northwestern Europe and the eastern Mediterranean is located at the 500 hPa level. Most parts of Iran are dominated by high pressure (*Fig. 13*-p2-A), and atmospheric stability conditions prevail (*Fig. 13*-p2-B). The PI index calculation also showed that the index was less than 1 in most parts of the country and the province of Khuzestan, and dry conditions have occurred (*Fig. 13*-p2-c).

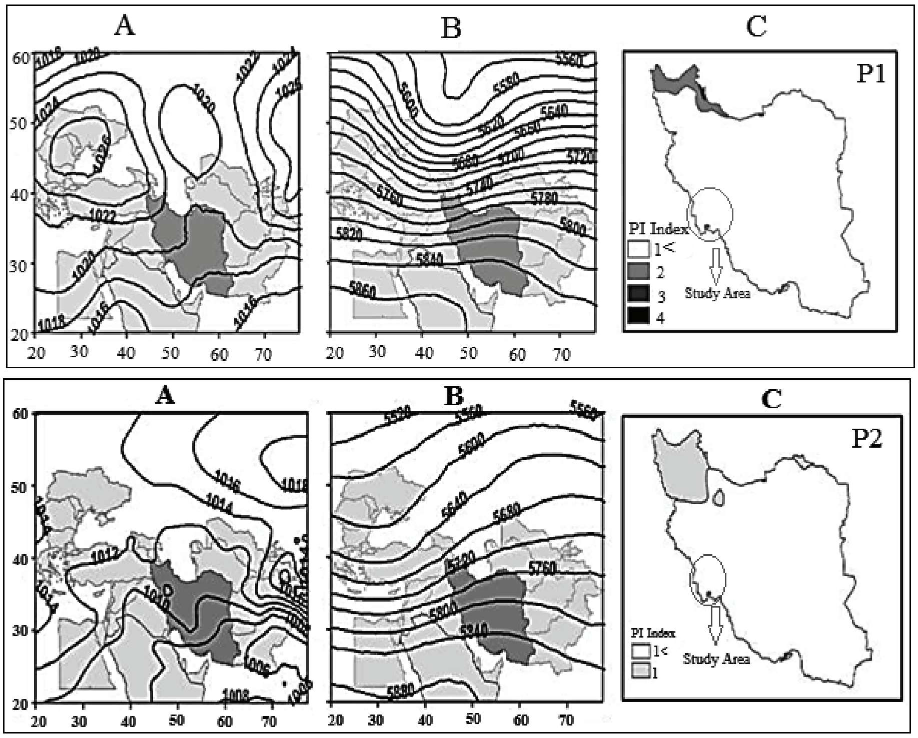

Fig. 13. Patterns of atmospheric circulation in Iran's Khuzestan province. A: 500 hPa mean geopotential height pattern ; B: mean sea level pressure pattern ;C: PI index pattern.

5.6. Evaluation of dry and wet periods

For the impact assessment of dry and wet periods in Khuzestan province, two sets of field data were used:

—data on groundwater levels in different parts of Khuzestan province,

—data on rainfed wheat yield in different parts of Khuzestan Province.

Data on groundwater levels and data relating to rainfed wheat yield were obtained from the Agricultural Research Center of Khuzestan Province. To evaluate the effects of dry days on water resources and agricultural products, 46 stations were selected. In order to evaluate the effect of the dry period, the water level and the correlation between these two parameters were studied, and linear regression and polynomial regression methods were used. The results of the correlation between the levels of the groundwater and the average probability of consecutive dry days in 46 selected stations showed that a significant, strong correlation exists between the mean probability of dry periods and the groundwater level. The degree of correlation is $R^2 = 0.93$ at a 99% confidence level (*Fig. 14*). This result shows that the groundwater is strongly influenced by dry periods.

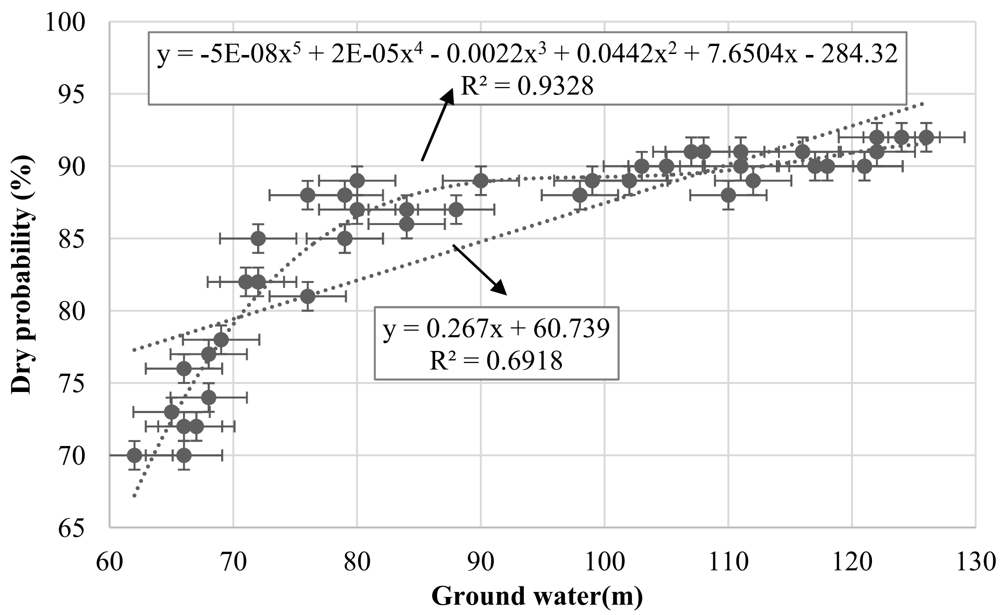

Fig. 14. Graph correlation between the average probability of dry periods and ground water levels.

In order to assess the impact of consecutive dry days on the yield of crops, rainfed wheat was selected, because it is the main crop of Khuzestan province, and its performance is subject to fluctuations in rainfall. The results of the regression relationship to calculate the average probability of dry days with an average annual yield of rainfed wheat in selected stations indicated the existence of a high correlation between these two parameters (at the 99% confidence level, $R^2 = 0.87$). Investigations showed that the yield of rainfed wheat is significantly reduced by increasing the probability of dry periods (*Fig. 15*).

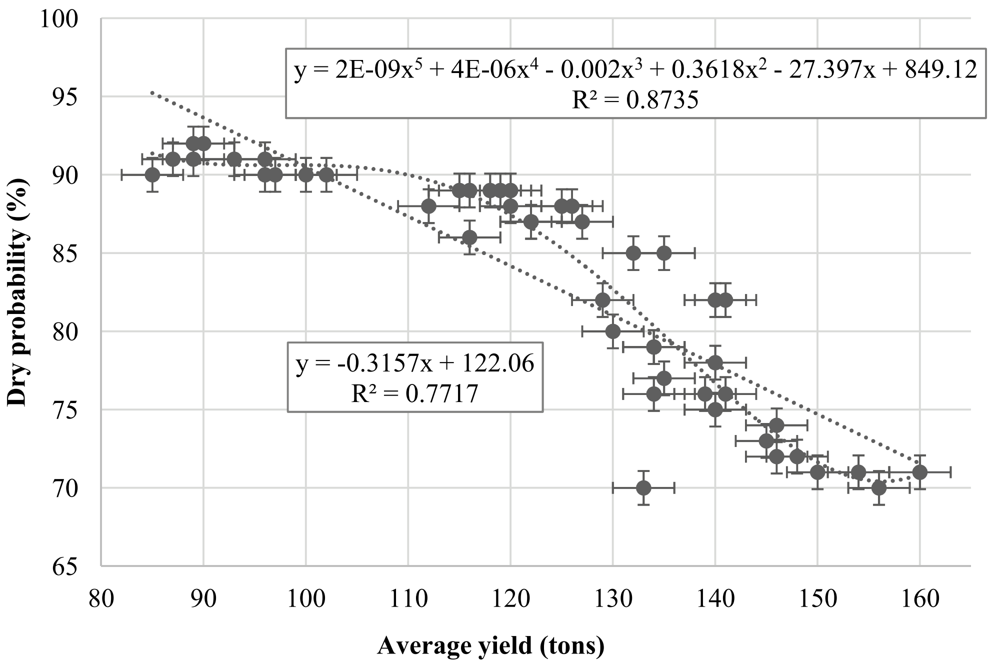

Fig. 15. Graph correlation between the average probability of dry periods and annual dryd wheat yield (tons).

6. Conclusions

The study of extreme precipitation events, such as floods and droughts, requires the analysis of wet and dry day sequences. The empirical frequency distribution does not provide a good insight into the probabilities of very long sequences of dry and wet spells, which are more important for practical purposes than short sequences. Statistical models give more reliable estimates. In this work, dry and wet spells were studied using the first-order Markov chain model. The daily precipitation data at 11 meteorological stations, being representative of different climate regimes in Khuzestan province, were analyzed. Wet or dry days were classified according to daily precipitation amounts of 1.0 mm.

Khuzestan province is one of the most important agricultural sectors with a variety of crops, and it plays an important role in supplying the needs of the country. This province is first in the country in cultivating cereals. Results of the current study showed that the probability of consecutive dry periods is high, in different parts of the province; moreover, water resources and agricultural performance are greatly affected by dry and wet periods, therefore, careful planning must be done in this area.

Results of the current study also indicate thaton the basis the generated sequences of wet and dry periods, the synoptic systems, and local factors (topography), four patterns were identified. Analysis of general circulation models of the atmosphere, and previous studies of this area by other researchers such as *Lashkari* (1996), *Alijani* (2002), *Hojatizadeh* (2002), and *Raziei et al.* (2008) confirm these conclusions. These patterns can predict extreme wet and dry periods.

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