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Comprehensive Regional Drought Assessment Index

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***Abstract*—**Drought is an inevitable part of the earth's climate. It occurs regularly with no clear warning and without recognizing borders. In addition, its impact is cumulative and not immediately discernible. Iran is located in a semi-arid region where droughts occur periodically as natural hazard. Standardized Precipitation Index (SPI), Surface Water Supply Index (SWSI), and Palmer Drought Severity Index (PDSI) are three well-known indices which describe drought severity; each has its own advantages and disadvantages and can be used for specific types of drought. These indices take into account some factors such as precipitation, reservoir storage and discharge, temperature, and potential evapotranspiration in determining drought severity. In this paper, first all three indices are calculated in Aharchay river watershed located in northwestern part of Iran in East Azarbaijan province. Next, based on two other important parameters which are groundwater level and solar radiation, two new indices are defined. Finally, considering all five aforementioned indices, a combined drought index (CDI) is presented and calculated for the region. This combined index is based on all the meteorological, hydrological, and agricultural features of the region. The results show that the most severe drought condition in Aharchay watershed happened in Jun, 2004. The result of this study can be used for monitoring drought and prepare for the drought mitigation planning.

***Keywords*—**Drought, index variation, regional assessment, monitoring.

I. Introduction

DROUGHT is a phenomenon occurring in different locations by very dry to very humid climate condition in the world and when there is high water demand and consumption, it causes costs and damages rising [1]. Timeframe, extent, and impact are the three important characteristics of drought.

Using of an index is a general approach to express and assess the severity of drought. There are different indices consisting of specific parameters. They demonstrate the hydrological, meteorological and hydraulic variables. SPI, PDSI, and SWSI are the main meteorological, hydrological, and agricultural drought indices that have been used in the world [2]. SPI was introduced by McKee (1993) [3] and includes the long-term record precipitation (at least 30 years) that will be normalized to special time scale. Due to its strong historic data, it can provide early warning of drought. SPI is a probability index and when it is below zero, it means that the region experience drought. PDSI offered by Palmer (1965) [4] is widely used to determine the agricultural drought. This index was developed with the aim of measuring the cumulative outflow of surface water balance. It gathers precipitation, temperature, and soil moisture data into hydrological accounting system. Shafer and Dezman (1982) provided SWSI index using for frequency analyze to normalize long-term data [5]. The PDSI could not be used when there is another source (such as snow pack), so SWSI can be used in these conditions [6]. Each of these indices illustrates only one or two aspects of the drought severity. So, combining the main indices results in a better drought expression. There are other parameters that have important effects in drought which have not been used in the main indices (SPI, SWSI and PDSI), such as groundwater level and solar radiation. Therefore, adding these parameters as another index, results in comprehensive index. While the effective parameters caused drought severity variations, they do not have a similar impact. Hence, these parameters should be weighted.

The main goal of this paper is to provide a comprehensive drought index by combining SPI, SWSI, and PDSI indices in order to include all aspects of drought severity. These three indices will be combined with new indices, and AHP method is used for weighting the impact of parameters.

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II. Case Study

The Aharchay river watershed, located in northwestern part of Iran in East Azerbaijan province, has been considered as the case study in this paper. The area location is between 38°10' and 38°45' N and 46°20' and 47°40' with the approximate area of 2381 km^2 as shown in Fig. 1. The Aharchay River with the length of 1100 km is located along the east-west direction and discharges into the Satarkhan Reservoir. The Satarkhan dam was constructed for meeting the domestic, industrial, agricultural, and environmental needs of the Ahar City [7]. According to the 18 years of recorded data from the synoptic Ahar, the mean rainfall of this region is about 291.1 millimeters. The mean temperature is 11.1 centigrade with the lowest 4.8 degree and highest 28 degree recorded [8].

III. Methodology

In the following section, the procedure for calculating SPI, SWSI, PDSI, and the new indices is presented and finally the combined index is proposed.

A. SPI, SWSI and PDSI Indices

The first drought index studied in this paper is the SPI developed. It is based on the distribution function curve of precipitation which provides early drought warning and it needs less data and calculation in comparison with the other indices. For computing this index, a probability distribution is fitted to long-term time series of precipitation and then transforms into normal distribution.

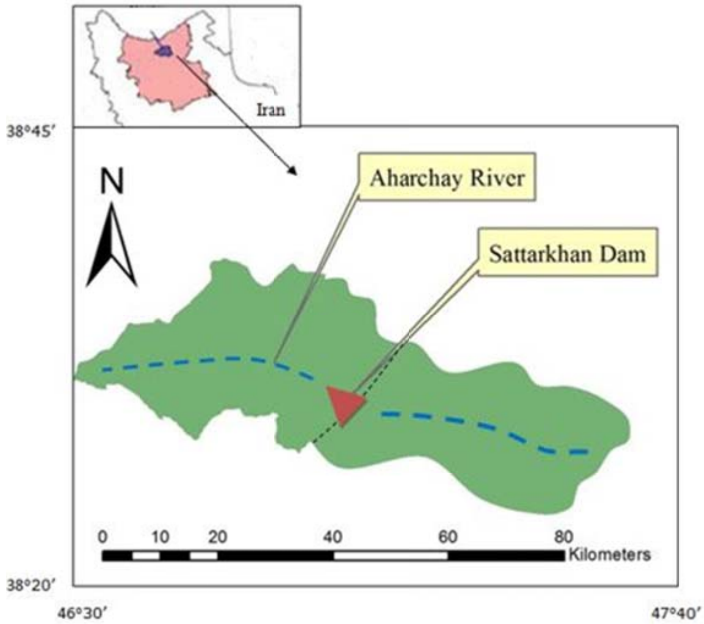

Fig. 1 Aharchay watershed Location (adapted from [7])

It has been proven by experience that probability distribution of precipitation in stations often follows gammas distribution with subsequent cumulative distribution function.

$$F(x) = \frac{1}{\Gamma(\hat{\alpha})}\int_0^x t^{\hat{\alpha}-1}e^{-t}dt \tag{1}$$

where x is the amount of variable, α shape parameter, β scale parameter and Γ(α) gamma function. In this study first, a gamma distribution is fitted to the monthly observed precipitation values. Next, the cumulative gamma distribution function is transformed into a cumulative Gaussian distribution (standard normal distribution with mean zero and variance of one), which gives the value of the SPI for the appropriate time scale. The best way of transforming a variable from one distribution function to another is to assume that the probabilities of less than the given variable in both distributions are equal. In Fig. 2, the SPI determination is shown.

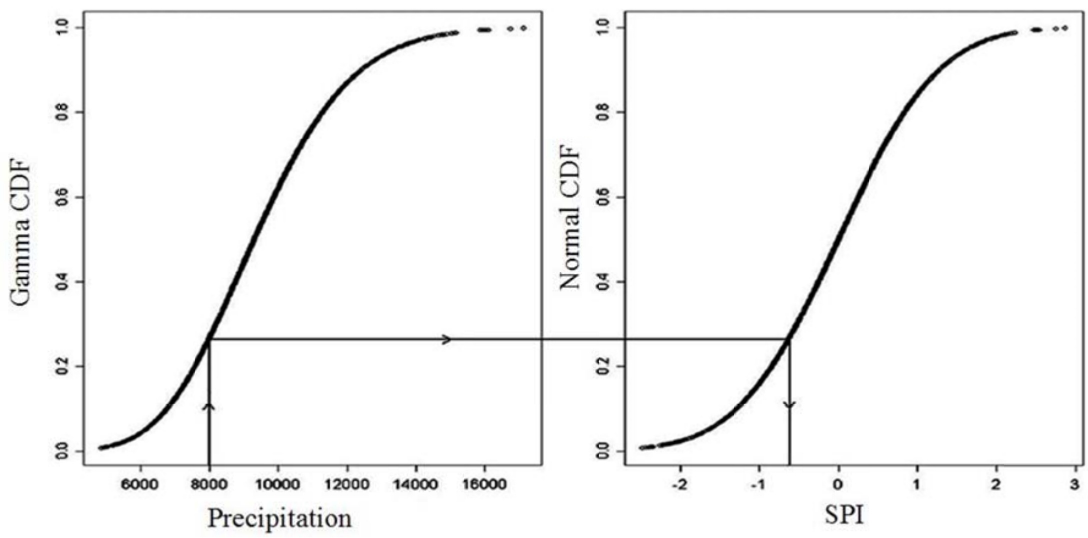

Fig. 2 The transformation of Gamma to normal distribution in SPI

Positive SPI values indicate greater than median precipitation, while negative values indicate less than median precipitation.

Palmer drought Index (PDSI) is the second considered drought index in this study. PDSI is one of the most common indices in the agricultural drought which shows the lack of soil moisture supply in the particular place and time. The main steps in PDSI calculation are:

1- Using water balance equation to compute the long term monthly soil moisture deficit or excess,
2- Estimating the constants and coefficients dependent on the region based on the result of water balance model,
3- Determining the difference between real and calculated moisture and converting this diversion to a comparable temporal index,
4- Analyzing indices time series for specifying a relation for calculating the drought severity (PDSI).

In the first step, Thornthwaite model is used to estimate the potential evapotranspiration. In the second step, the following coefficients were obtained.

$$\alpha = \frac{\overline{ET}}{\overline{ET_p}} \quad (2)$$

$$\beta = \frac{\bar{R}}{\overline{PR}} \quad (3)$$

$$\gamma = \frac{\overline{RO}}{\overline{PRO}} \quad (4)$$

$$\delta = \frac{\bar{L}}{\overline{PL}} \quad (5)$$

where ETp is the potential evapotranspiration, PR potential recharge, PRO potential runoff, PL potential loss. ET, R, RO, and L are the average evapotranspiration, recharge, runoff, and loss for each month during study time period, respectively. Next, moisture index is calculated based on the difference between real and climatically appropriate precipitation (6)-(9):

$$Z = dk \quad (6)$$

$$d = P - \hat{P} \quad (7)$$

$$\hat{P} = ET + R + RO - L \quad (8)$$

$$k = \frac{\overline{ET}+\bar{R}+\overline{RO}}{\bar{P}+\bar{L}} \quad (9)$$

where $\hat{P}$ is the climatically appropriate precipitation. Finally, based on the value of moisture index, the PDSI index is calculated (10):

$$PDSI_i = (1 - c) * PDSI_{i-1} + \frac{Z_i}{a+b} \quad (10)$$

Based on the research of Steineman [9], the value of C and a+b is considered as 0.103 and 3 for dry weather, respectively.

The other index used in this study is SWSI which is an imperative index in hydrological drought. It was first introduced based on four parameters: snow, river discharge, precipitation, and reservoir volume. Due to some limitations such as the difficulty of estimating snow melting, the modified version of SWSI proposed by Garen was used (11) [10]:

$$SWSI = \frac{P-50}{12} \quad (11)$$

where p is the probability calculated from the distribution function fitted to the summation of predicted river discharge and reservoir volume.

B. Standardized Groundwater Index (SGI)

The groundwater resources are important alternatives of water resources in the region, particularly at the time of drought. In this study, the groundwater level time series in Aharchay watershed is considered for 11 years (2004-2014). Then, after fitting several distribution functions to the groundwater level data, the best fitting distribution is determined and finally, it transforms into normal distribution (same as the procedure for SPI method).

C. Standardized Solar Radiation Index (SSI)

Solar radiation is another factor that is considered owing to its significance in evaluating evapotranspiration. Because of low number of solar radiation sites and lack of accuracy in direct measurement of solar radiation, particularly with old tools in Iran, a number of empirical formula have been improved, each needs especial input data, to estimate daily or monthly global radiation at different places in the world (such as [11]-[14]).

In this study, Sabbagh method has been used due to availability of data in Iran (12). This model can be applied to dry arid and semi-arid regions such as Iran.

$$R_{est} = 0.06407(K_g)\exp[L(\frac{n}{12} - \frac{RH^{0.333}}{100} - \frac{1}{T_{max}})] \quad (12)$$

where R_{est} is the estimated total daily global radiation ($MJ.m^{-2}.day^{-1}$) at a horizontal surface, n the monthly average daily real sunshine duration (hr) measured by Campbell-Stokes sunshine recorders, RH the relative humidity (%), Tmax the monthly average of daily maximum air temperature (°C) and kg the geographical factor ($g.cal.cm^{-2}.day^{-1}$) of Sabbagh method as suggested by Reddy [15]:

$$K_g = 100(\lambda N + \psi_{i,j} cosL) \quad (13)$$

where L is latitude of the place in degrees, N the monthly average of daily maximum possible sunshine duration in hour, and λ the latitude factor which is estimated as:

$$\lambda = \frac{0.2}{(1+0.1L)} \quad (14)$$

$\psi_{i,j}$ is the seasonal factor (i=1,2,3 for inland station, coastal stations and hilly stations respectively while j=1,2,3,…,12 is the month index from January to December) suggested by Reddy [15].

D. Combined Drought Index (CDI)

For developing a comprehensive index which could take into account all aforementioned indices in meteorological, hydrological, and agricultural droughts, the following CDI is proposed:

$$CDI = W_1 * SPI + W_2 * PDSI + W_3 * SWSI + W_4 * SGI + W_5 * SSI \quad (15)$$

The weights in (15), which show the importance of each index, were obtained based on AHP method which uses the expert's opinion. Due to the fact that the range of each index is different, each of them was first standardized between zero and one and then the standardized CDI (SCDI) was calculated.

IV. Results

In this paper, 5 indices which are SPI, PDSI, SWSI, SGI, and SSI have been computed for 11 years (2004-2014). Fig. 3 shows variety of aforementioned indices. Table I shows the range and weights of these indices.

TABLE I
RANGE OF SPI, PDSI, SWSI, SGI AND SSI INDICES

Index	SPI	PDSI	SWSI	SGI	SSI
Range	-2.83 to 2.50	-8.96 to 7.63	-4.13 to 3.83	-1.55 to 2.25	-5.32 to 2.06
Weight	0.1	0.4	0.2	0.15	0.15

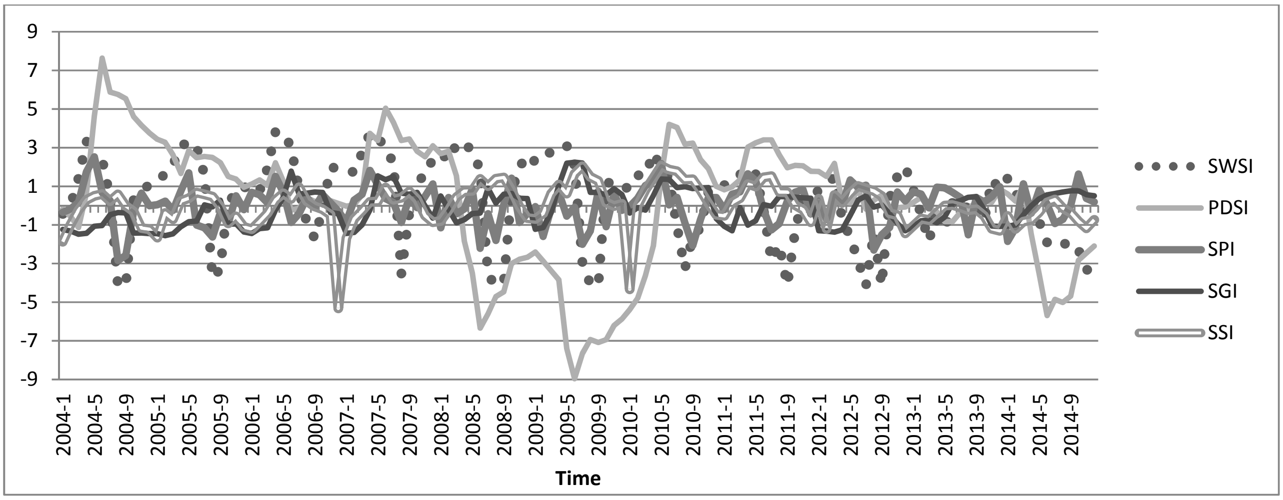

Fig. 3 Variation of SPI, PDSI, SWSI, SGI and SSI indices

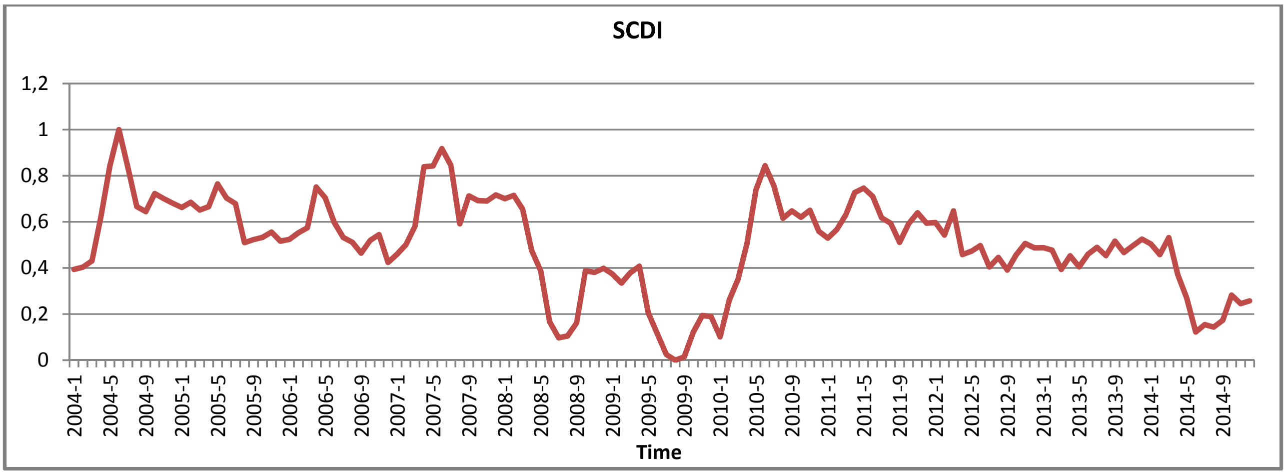

Fig. 4 Standardized CDI variation

SCDI helps monitoring drought with various parameters, not just temperature and precipitation. Besides, it takes into account different types of drought (meteorological, hydrological, and agricultural drought). As it can be seen in Fig. 4, SCDI changes between 0 and 1 which shows that Aharchay watershed experiences different climate conditions. The most severe drought condition has been occurred in Jun, 2004.

V. Summary and Conclusion

In this study, different drought indices were calculated in Aharchay watershed located in Iran, and a CDI has been proposed. For this purpose, firstly, three well-known drought indices which are SPI, PDSI and SWSI were calculated. Next, two new indices which are the standardized groundwater index (SGI) and the standardized solar radiation index (SSI) were defined and computed. Finally, CDI which is the weighted summation of all aforementioned indices was calculated.

It can be concluded that CDI could be used by the decision-makers to monitor and predict the severity of drought comprehensively based on the meteorological, hydrological, and agricultural features of the region and prepare a mitigation plan for this hazard.

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