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An Investigation and assessment of meteorological drought in Lake Urmia Basin using drought indices and probabilistic methods

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Abstract
Drought is one of the most important weather-induced phenomena which may have severe impacts on different areas such as agriculture, economy, energy production, and society. A number of drought indices have been introduced and used in various countries to date. In the current study, four meteorological drought indices including Percent of Normal Precipitation Index (PNPI), Standard Index of Annual Precipitation (SIAP), Rainfall Anomaly Index (RAI), and Standardized Precipitation Index (SPI) are compared and evaluated for monitoring droughts in Lake Urmia Basin in Iran. The comparison of indices was carried out based on drought classes that were monitored in the study area using 40 years of data (1966-2005). Two well-known probability approaches including Runs theory and Markov chain model, were used to estimate the probability of wet and dry periods. The frequency matrix is formed and the transition probability matrix of wet- dry spells is created accordingly based on maximum likelihood method. The equilibrium probability is calculated based on succeed power on probability matrix. The results demonstrated that among the drought indices, PNPI is not an appropriate index in annual estimates and SPI and RAI are better than other indices and their results are nearer to reality. The results indicated the equilibrium probability of very dry, dry, normal, wet and very wet periods is obtained 0.23, 0.27, 0.23, 0.17 and 0.1, respectively.

Keywords
drought, Lake Urmia basin, Markov chain, PNPI, RAI, runs theory, SIAP, SPI.

1. Introduction
Climate change is one of the most significant issues facing the world because it is predicted to alter climate patterns and increase the frequency of extreme weather events (IPCC, 2012). In recent years, the frequency of droughts that are due to global warming-related climate change has increased and is accompanied by a rise in the severity of these phenomena (IPCC, 2013). Droughts are natural hazards that cause enormous damage to social and economic sectors all around the world, and their devastating effects to eco-environmental systems are still hard to determine. Droughts are complex events best characterized by a series of properties including their frequency, duration and intensity (Mishra & Singh, 2010). Droughts can be defined from various perspectives including meteorological, hydrological, agricultural, and socio-economical. In general, a drought is defined as a dry weather period that lasts over several weeks to months, with no or little accumulated rainfall. Such dry weather events have significant impacts on water resources, agriculture, forestry, hydro-power, health, and socioeconomic activities. A reduced

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amount of accumulated rainfall leads to low soil moisture and river flows, reduced storage in reservoirs and less groundwater recharge (Tallaksen & van Lanen, 2004). Thus, drought monitoring and prediction are of critical importance for developing measures to mitigate the impacts of droughts (Hao & Aghakouchak, 2014).

The preparedness and planning for a drought depend on the information about its areal extent, severity and duration (Mishra & Singh, 2011). This information can be obtained through drought monitoring that is usually done with the use of drought indices which provide information to decision makers about drought characteristics. Thus, these indices can be used to initiate drought action plans. Prediction of droughts is useful for early warning that may reduce the response time and consequently the impact of a drought.

Palmer (1965) introduced probably the first comprehensive drought index, known as the Palmer drought severity index (PDSI). Earlier drought indices were drought-definition specific but PDSI involves precipitation, temperature and soil moisture in a water balance model. PDSI gained prominence from the 1960s to the 1990s. Since then many other drought indices have been developed to quantify drought conditions throughout the world.

Keyantash and Dracup (2002) reviewed 14 well-known drought indices which have been used for assessing the severity of meteorological, hydrological, and agricultural droughts. Barua et al. (2011) also applied the same set of evaluation criteria except for dimensionality. Moreira et al. (2008) studied the drought at two regions of Alninjo and Agra in Southern Portugal and concluded that the drought extended during autumn and only in two months, SPI variants became near to severe drought class. Buntgen et al. (2010) studied the summer droughts in Germany, and stated that from a synoptic view, the positioning of an anticyclone system in the middle section of the atmosphere over the North Sea and a cyclone system over southeast Europe caused summer droughts. Mishra and Singh (2010) have pointed advantages and limitations of different indices. He et al. (2011) detected and assessed the spatial characteristics of drought in China using 3-month SPI and the phenology data of main grain crops. Their results revealed that the areas with high risk of drought hazard mainly are scattered in the southeast portion and the eastern agricultural area of Qinghai. Hao and AghaKouchak (2014) developed the multivariate standardized drought index (MSDI) through parametric and nonparametric copula approaches, which probabilistically combines the standardized precipitation index (SPI) and the standardized soil moisture index (SSI) for characterizing droughts.

In Iran, drought conditions have been documented in several studies. For example, Ramazani (2005) used standardized precipitation index as well as other indices which are used in studying drought with determination of deviation from long-term precipitation average. He also introduced numbers, which are dimensionless and are used in annual humid and drought analyses. Vafakhah and Rajabi (2005) have compared SPI with other indices including Percentage of normal precipitation (PNPI), Precipitation Deciles (DPI), Precipitation Abnormality and Z index in Bakhtegan basin and have reported DPI and PNPI indices that have less standardized deviation and more average. Morid et al. (2006) compared seven indices for drought monitoring in Tehran province of Iran. Percent of Normal (PN), Rainfall Deciles (RDs), Statistical Z Score (Z-Score), Standardized Precipitation Index (SPI), China-Z Index (CZI), Modified China-Z Index (MCZI), and Effective Drought Index (EDI) were used. These indices are all rainfall-based and are able to quantify both dry and wet cycles. Comparisons showed that SPI and EDI performed better in detecting the onset of drought, and these were recommended to the Tehran drought monitoring system. This study is enlightening and currently one of the most exhaustive comparison studies. Karimpour Reyhan et al. (2009) analyzed drought event and its emerging regions using Standardized Precipitation Index (SPI) in Markazi desert, with focus on Semnan province. The results showed that there was drought condition in 17 studied stations. Also among 44 stations with no drought condition, there was one humid year in 20 cases. Asefjah et al. (2014) compared drought indices including the standardized precipitation index (SPI), China-Z index (CZI), modified CZI (MCZI) and Z-Score (Z) for monitoring droughts in Salt Lake Basin in Iran. They concluded that by considering the advantages and disadvantages of the mentioned drought predictors in Iran, the CZI and Z-Score could be used as good meteorological drought predictors.

Droughts are considered to be multi-faceted extreme events that can inflict considerable damage to the human society in many ways. Therefore, proper understanding of the spatial and temporal characteristics of historical droughts is needed for many water resources and agriculture planning and management related activities in order to mitigate their harmful effects on communities. This study is focused specifically on the Lake Urmia Basin (Fig. 1) that is located in Northwest of Iran, where agricultural activities are concentrated. In this regard, the purpose of this paper was to compare the performance of several rainfall-based drought indices and assess the drought conditions using Markov chain and Runs approach for Lake Urmia Basin.

2. Study area

The Lake Urmia Basin is located between 37°4′ to 38°17′ latitude and 45°13′ to 46° longitude in northwest Iran and covers an area of 51,800 km^2 which covers 3.15 % of the entire country and includes 7% of the total surface water in Iran (Fig. 1). The Lake Urmia is the largest lake in the country and is also the second hyper saline lake (before September 2010) in the world. The lake basin includes 14 main sub basins that surround the lake with the areas varying from 431 to 11,759 km^2. The most important rivers in this basin are Zarrineh Roud, Simineh Roud, and Aji Chai (Fathian et al., 2015). Climate in the Urmia Lake Basin is continental, affected mainly by the mountains surrounding the lake. The Lake Urmia is located between two provinces, namely West-Azararbayjan and East Azarbayjan. The difference between the highest and lowest parts of the basin is about 2,576 m. The average of rainfall on the basin is about 398 mm. This basin had the second rank in receiving large annual rainfall among all main watersheds in Iran.

In this study, six weather stations listed in Table 1 are selected to provide a broad range of coverage in the region in terms of data length, homogeneity, and geographical distribution. For this study, data was obtained from the database of the Islamic Republic of Iran Meteorological Organization (IRIMO) and annual precipitation (1966- 2005) were used to compute drought indices.

Table 1. List of stations with latitude, longitude, altitude and time period in the study area

station	Longitude (E)	Latitude (N)	Altitude(m)
Mahabad	45° 43´	36° 46´	1500
Maragheh	46° 16´	37° 24´	1477.7
Oroomieh	45° 05´	37° 32´	1316
Saghez	46° 16´	36° 14´	1552.8
Sarab	47° 32´	37° 56´	1682
Tabriz	46° 17´	38° 05´	1361

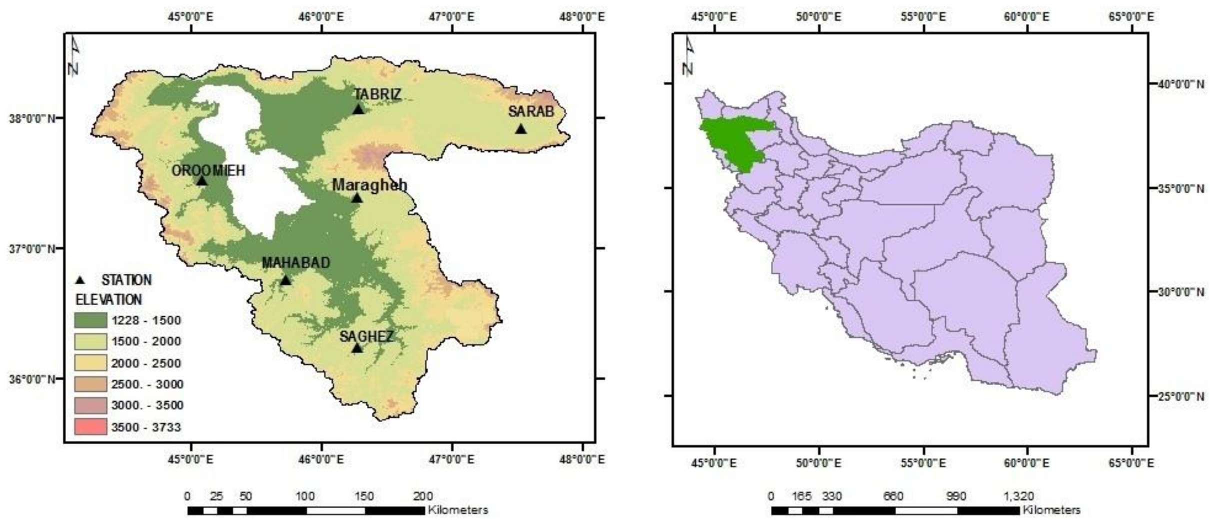

Fig. 1. The DEM and location of meteorological stations in the Lake Urmia Basin

3. Materials and Methods

3.1. Drought indices

A good number of indices have been suggested and used for detection and monitoring of meteorological, agricultural, hydrological and socio-economical drought. These indices include the PDSI (Palmer, 1965), Palmer Hydrological Drought Index (Palmer, 1965), Z-Index (Palmer, 1965), Rainfall Anomaly Index (RAI) (Van Rooy, 1965), the Drought Severity Index (DSI) (Bryant et al., 1992), SPI (McKee et al., 1993), the Reconnaissance Drought Index (RDI) (Tsakiris et al., 2007), Standardized Runoff Index (SRI) (Shukla & Wood, 2008), SPEI (Vicente-Serrano et al., 2010), Rainfall Variability Index (RVI) (Oguntunde et al., 2011), Multivariate Standardized Drought Index (Hao & AghaKouchak, 2013), and other variants of some commonly used drought indices. As already indicated, there is no consensus among the scientific community engaged in drought research on the selection of a drought index. Generally, the choice of an index is driven by the availability of relevant observed data and ease of computation and interpretation of the results obtained. Also, to some extent, the choice of the index is driven by the desired targets of a given project (Mishra & Singh, 2010). In the present study, four drought indices, namely the PNPI, SIAP, RAI and SPI, are used. All indices represent the so called meteorological drought.

3.1.1. Percentage of normal precipitation index (PNPI)

The percent of normal precipitation is a simple measurement of precipitation for a given location. Identification of the trend of drought by the percent of normal is very descriptive for a single region or a single season. This index can be calculated for a variety of time scales (a single month, a group of months representing a particular season and annual or water year). Normal precipitation for any given location is considered to be 100%. This index is calculated as Equation (1).

$$PN = \frac{P_i}{\bar{P}} \times 100 \tag{1}$$

where P_i is actual precipitation and $\bar{P}$ is normal precipitation. Table 2 shows the PNPI thresholds by Willeke et al. (1994).

3.1.2. Standardized index annual precipitation (SIAP)

The best method for transferring raw data of precipitation to relative amounts is that the deviation of precipitation from mean shall be divided to standard deviation. In this regard, Khalili (1991, 1998) provided the standard index precipitation is as followed for studying the process of drought and wet periods in Iran. This index, in addition to the mean, considers the standard deviation. The SIAP may be negative (dry) in some stations, and positive (wet) in others, due to the different pluvial systems in various parts of the country.

The values of Standard Index of Annual Precipitation (SIAP) can be computed by using Equation (2).

$$SIAP = \frac{Pi - \bar{P}}{SD} \tag{2}$$

where P_i is the annual rainfall in i_{th} year; $\bar{P}$ is the average rainfall; and SD is the standard deviation observed for rainfall during study period. The SIAP index is without dimensions and its value ranges between -3 and +3. A smaller value of SIAP indicates a more severe drought and as it becomes larger, the drought is less severe. Table 2 shows the drought categories in relation to the SIAP index.

3.1.3. Rainfall anomaly index (RAI)

Among different indices of drought monitoring, rainfall anomaly is the most effective and simple meteorological drought index. This index was introduced by Van Rooy (1965). This index is based on the calculation of the rainfall in comparison to accidental numbers from -3 to +3. The only parameter to calculate this index is rainfall. In RAI, the data is sorted from the largest to the smallest, then by calculating the average of the ten largest and the ten smallest values of rainfall during the statistical period, the drought is described according to the following relations. In this method RAI > -0.3 shows a normal condition and RAI ≤ -0.3 shows drought with varying severities (Van Rooy, 1965)

$$RAI = 3\left[\frac{P - \bar{P}}{\bar{m} - \bar{P}}\right] \qquad if\ : P > \bar{P} \tag{3}$$

$$RAI = -3\left[\frac{P - \bar{P}}{\bar{X} - \bar{P}}\right] \qquad if\ : P < \bar{P} \tag{4}$$

where X is the average of the ten smallest values of rainfall, M is the average of the ten largest values of rainfall, $\bar{P}$ is the long-term average rainfall, and P is the value of rainfall. The categorization of drought based on RAI is given in Table 2.

3.1.4. Standardized precipitation index (SPI)

The standardized precipitation index (SPI) was developed for the purpose of defining and monitoring droughts (McKee et al., 1993). It is based on the long-term monthly precipitation data at a given period. After fitting a Gamma distribution and transforming it to a normal distribution by an equal probability transformation, the SPI is computed as the precipitation anomaly of the transformed data, divided by the standard deviation of the transformed data (Huang et al., 2014). SPI is calculated using the following equation (McKee et al., 1993):

$$SPI = \frac{Pi - \bar{P}}{S} \tag{5}$$

where P_i is the annual rainfall amount, $\bar{P}$ is the average long-term rainfall, and S is standard deviation of the rainfall.

Once the SPI is calculated, the intensities of dry and wet events are classified as displayed in Table 2. The SPI can track dry/wet events on different time-scales, i.e. 1-, 3-, 6-, 12-, and 24-months, and is flexible with respect to the period chosen (Bordi et al., 2004; Raziei et al., 2009). In 2009, WMO recommended SPI as the main meteorological drought index that countries should use to monitor and follow drought conditions (Hayes, 2011). By identifying SPI as an index for broad use, WMO provided direction for countries trying to establish a level of drought early warning.

Table 2. Drought categories in PNPI, SIAP, RAI and SPI

Category	PNPI	SIAP	RAI	SPI
Near normal	More than 80 %	-0.25 to 0.25	-0.3 to 0.3	-0.99 to 0.99
Slight drought	70 - 80 %	-0.52 to -0.25	-1.2 to -0.3	-
Moderate drought	55 - 70 %	-0.84 to -0.52	-2.1 to -1.2	-1.00 to -1.49
Severe drought	40 – 55 %	-1.28 to -0.84	-3 to -2.1	-1.5 to -1.99
Extreme drought	Less than 40 %	-1.28 and less	-3 and less	-2.00 and less

3.2. Probabilistic methods

3.2.1. Runs theory

Runs theory is the threshold-level method presented by Yevjevich (1967), which defines droughts as periods during which the flow is below a certain threshold level. The method is based on the statistical theory of Runs for analyzing a sequential time series. Yevjevich (1967) proposed this theory for identifying drought parameters and investigating their statistical properties of the distributions of water deficits: (a) run-length (drought duration), (b) run-sum (deficit volume) or magnitude, and (c) severity or intensity. The most basic element for deriving these parameters is the truncation, or threshold level, which may be a constant or a function of time. A run is defined as a portion of the time series of a drought variable, X_t, in which all values are either below or above the selected truncation level of X_0, accordingly called either a negative run or a positive run. The timing of a drought has several different definitions; it can be defined based on the starting date of the drought, the mean onset of the drought, the termination date of the drought, or the date of minimum drought index value. The drought duration is considered to be the time period between the initiation and termination of a drought. The theory of runs has received considerable attention in the study of droughts (Yevjevich, 1967; Panu & Sharma, 2009; Nam et al., 2015). Categorization of dry periods based on this index is shown in Table 3.

Table 3. The amounts of thresholds based on the Runs theory

Category	Symbol	Threshold
Very Wet	VW	409 and above
Wet	W	346.5 – 409.5
Normal	N	283.5- 346.5
Dry	D	220.5- 283.5
Very Dry	VD	220.5 and below

3.2.2. Markov chain

A Markov chain (Çinlar, 1975) is a stochastic process X, such as at any time t, X_{t+1} is conditionally independent from X_0, X_1, X_2, ..., X_{t-1}, given X_t; the probability that X_{t+1} takes a particular value j depends on the past only through its most recent value X_t.

The most common form of Markov chain is the first-order Markov chain, where the transition probabilities controlling the next state of the system depend only on the current state of the system. This characteristic of first-order Markov chains is known as the Markovian property, which can be expressed more formally as (Wilks, 2011):

$$\Pr\{X_{t+1}|X_t,X_{t-1},X_{t-2}, \dots ,X_1\} = \Pr\{X_{t+1}|X_t\}$$

The occurrence of wet or dry day is influenced by the status of previous day. The first-order Markov chain is used here to describe the occurrence of wet and dry days and its transition frequency matrix (N) and transition probability matrix (P) is represented as follows.

$$N = \begin{bmatrix} N_{11} & N_{12} & N_{13} & N_{14} & N_{15} \\ N_{21} & N_{22} & N_{23} & N_{24} & N_{25} \\ N_{31} & N_{32} & N_{33} & N_{34} & N_{35} \\ N_{41} & N_{42} & N_{43} & N_{44} & N_{45} \\ N_{51} & N_{52} & N_{53} & N_{54} & N_{55} \end{bmatrix}$$

$$P = \begin{bmatrix} P_{11} & P_{12} & P_{13} & P_{14} & P_{15} \\ P_{21} & P_{22} & P_{23} & P_{24} & P_{25} \\ P_{31} & P_{32} & P_{33} & P_{34} & P_{35} \\ P_{41} & P_{42} & P_{43} & P_{44} & P_{45} \\ P_{51} & P_{52} & P_{53} & P_{54} & P_{55} \end{bmatrix}$$

with $P_{11} + P_{12} + \ldots + P_{15} = 1$ and etc.

The transition probabilities are estimated using the method of maximum likelihood (Kannan & Farook, 2015).

$$P_{ij} = \frac{n_{ij}}{\sum_{j=0,1} f_{ij}} \tag{6}$$

where n_{ij} is the historical frequency of transition from state i to state j.

4. Results and Discussion

4.1. Drought indices

The results of drought monitoring in Lake Urmia Basin using Percentage of Normal Precipitation Index (PNPI) are given in Table 4 and the time series of PNPI values are given in Figure 2. Table 4 shows that the drought has occurred in Lake Urmia basin with various severities in 8 years (20%). In 1989 and 2005 slight drought and in 1970, 1973, 1990, 1999, 2000, and 2001 moderate drought has happened. It is notable that PNPI has not estimated any kind of extreme and severe drought that is far from the reality. The most severe drought occurred in 1999 with the PNPI value of 61.3% and the weakest drought occurred in 2005 with a PNPI value of 73.4% (Fig. 2).

The results of Standardized index annual precipitation (SIAP) show that in the Lake Urmia basin 16 droughts periods (40%) have occurred with various severities in 1966-2005. SIAP show four slight droughts (1983, 1985, 1997 and 2003), four moderate droughts (1971, 1975, 1995 and 1998), three severe droughts (1973, 1989 and 2005) and five extreme droughts (1970, 1990, 1999, 2000 and 2001) in Lake Urmia basin. The most severe drought occurred in 1999 with the SIAP value of -1.57 and the weakest drought occurred in 1985 with a SIAP value of -0.27. The longest drought duration has occurred for 4 years from 1998 to 2001, that in 1998, the slight drought and in the other years has happened the extreme drought (Table 5, Fig. 3).

The results of drought monitoring in Lake Urmia Basin using Rainfall Anomaly Index (RAI) are given in Table 6 and the time series of RAI values are given in Figure 4. The results show that the drought has occurred in 19 years (47.5%) in Lake Urmia basin. RAI show seven slight droughts (1966, 1978, 1983, 1985, 1996, 1997 and 2003), four moderate droughts (1971, 1975, 1995 and 1998), three severe droughts (1973, 1989 and 2005) and five extreme droughts (1970, 1990, 1999, 2000 and 2001) in the study area. The most severe drought occurred in 1999 with the RAI value of -3.84 and the weakest drought occurred in 1978 with a RAI value of -0.36. Based on RAI, the longest drought duration has occurred for seven years from 1995 to 2001, that in 1996 and 1997, the slight drought, in 1995 and 1998 the Moderate drought and in 1999, 2000 and 2001 the extreme drought has happened (Table 6 and Fig. 4).

Table 4. Drought monitoring in Lake Urmia basin using PNPI

Category	PNPI (%)	Frequency	Frequency (%)
Near normal	More than 80	32	80
Slight drought	70-80	2	5
Moderate drought	55-70	6	15
Severe drought	40-55	0	0
Extreme drought	Less than 40	0	0

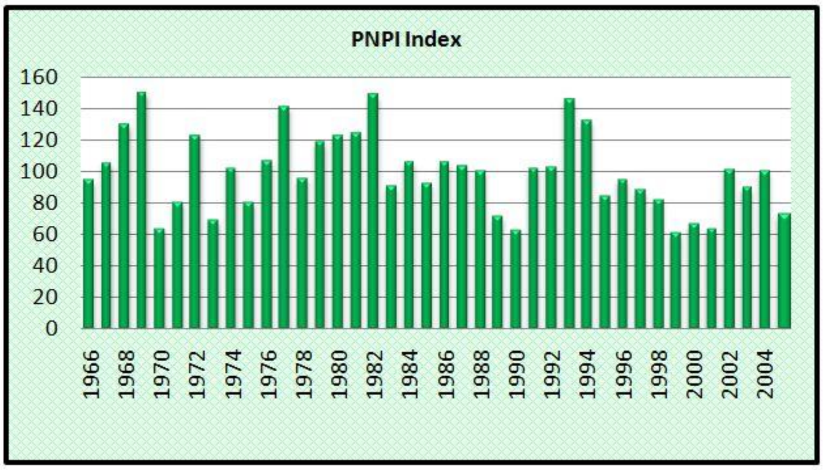

Fig. 2. Time series of PNPI values in Lake Urmia basin

Table 5. Drought monitoring in Lake Urmia basin using SIAP

Category	SIAP	Frequency	Frequency (%)
Near normal	-0.25 to 0.25	24	60
Slight drought	-0.52 to -0.25	4	10
Moderate drought	-0.84 to -0.52	4	10
Severe drought	-1.28 to -0.84	3	7.5
Extreme drought	-1.28 and less	5	12.5

Table 6. Drought monitoring in Lake Urmia basin using RAI

Category	RAI	Frequency	Frequency (%)
Near normal	-0.3 to 0.3	21	52.5
Slight drought	-1.2 to -0.3	7	17.5
Moderate drought	-2.1 to -1.2	4	10
Severe drought	-3 to -1.2	3	7.5
Extreme drought	-3 and less	5	12.5

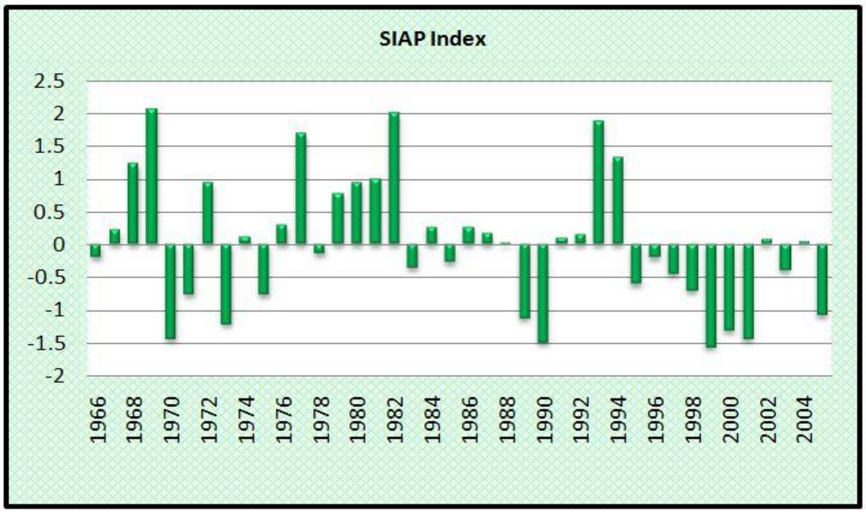

Fig. 3. Time series of SIAP values in Lake Urmia basin

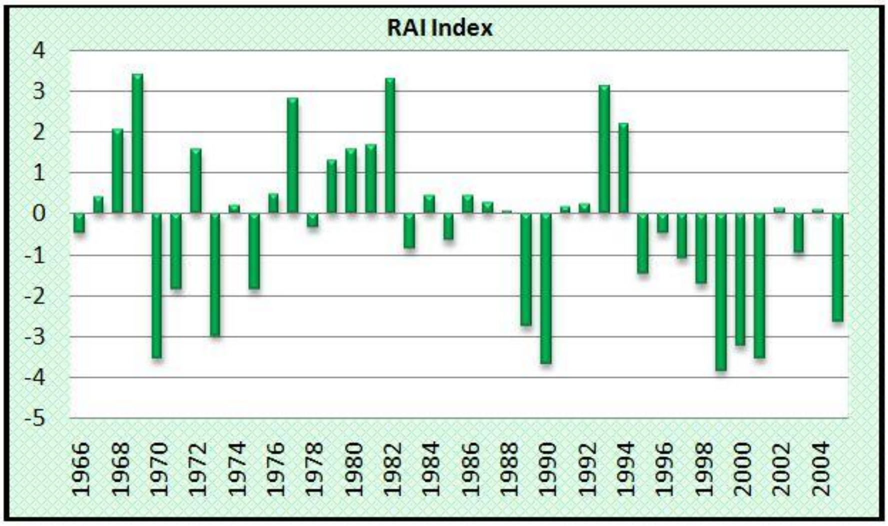

Fig. 4. Time series of RAI values in Lake Urmia basin

The results from the Standard Precipitation Index (SPI) show that there were 19 dry periods with different severities in Lake Urmia basin for 1966-2005. Based on SPI, there were seven slight droughts (1966, 1978, 1983, 1985, 1996, 1997 and 2003), four moderate droughts (1971, 1975, 1995 and 1998), six severe droughts (1970, 1973, 1989, 2000, 2001 and 2005) and two extreme droughts (1990 and 1999). The most severe drought occurred in 2001 with the SPI value of -1.97 and the weakest drought occurred in 1978 with a SPI value of -0.57. As RAI, the longest drought duration has occurred for seven years from 1995 to 2001, with the difference that the extreme drought can be seen only in 1999 and in 2000 and 2000 the severe drought has occurred (Table 7 and Fig. 5).

According to the results of drought indices, the lowest number of drought (8), equivalent to 20%, is calculated by PNPI and the highest number of droughts (19), equivalent to 47.5%, is calculated by RAI and SPI. In most of the indices, the slight and moderate droughts are more frequent. Approximately every ten years, a severe drought takes place in the Lake Urmia basin. The results of SIAP, RAI and SPI are similar approximately, but they are different from PNPI. PNPI has not estimated any kind of extreme and severe drought that is far from the reality. It seems that PNPI is not an appropriate index in annual estimates and an increase in time period is an obstacle to PNPI estimates. A similar result has also been reported by Willeke et al. (1994). RAI considers the extreme changes mostly and performs well in estimating the extreme drought and wet periods. Therefore, in areas with high rainfall variability, the anomaly index is better than other indices and its results are nearer to reality.

4.2. Probabilistic methods

In this study to investigate the occurrence and persistence probability of droughts in Lake Urmia basin, The annual rainfall situation was determined using Runs theory from 1966-2005 (Table 7). Then the frequency of different drought periods and the percentage of each of them were calculated for the basin (Table 8). Based on Runs theory, there are eleven normal years, eleven dry years, eight very dry years, six wet years and four very wet years. So, the drought has occurred in 19 years (equivalent to 47.5%) in Lake Urmia basin. These results correspond to the SPI and RAI results. Trend of wet and dry periods in this basin is shown in Figure 5.

Table 7. The severity of dry and wet periods in the Lake Urmia basin using Runs theory

Year	Annual rainfall	Symbol	Year	Annual rainfall	Symbol
1966	272.7	D	1986	314.8	N
1967	311.4	N	1987	305.3	N
1968	401.6	W	1988	292.8	N
1969	474.5	Vw	1989	189.5	Vd
1970	160.7	Vd	1990	156.5	Vd
1971	222.2	D	1991	299.4	N
1972	375.5	W	1992	303.6	N
1973	181.6	Vd	1993	458.6	Vw
1974	330.2	N	1994	409.4	W
1975	221.8	D	1995	236	D
1976	316.7	N	1996	272.4	D
1977	442.2	Vw	1997	249.8	D
1978	277.6	D	1998	227	D
1979	360.2	W	1999	150.2	Vd
1980	375.3	W	2000	172.5	Vd
1981	380.4	W	2001	161	Vd
1982	469.8	Vw	2002	297.4	N
1983	258.5	D	2003	255	D
1984	313.9	N	2004	295.1	N
1985	266.1	D	2005	194	Vd

Table 8. Frequency and percentage of frequency for wet and dry periods in Lake Urmia basin

Category	Threshold	Frequency	Frequency (%)
Very wet	409 and above	4	10
Wet	346.5 – 409.5	6	15
Normal	283.5- 346.5	11	27.5
Dry	220.5- 283.5	11	27.5
Very dry	220.5 and below	8	20

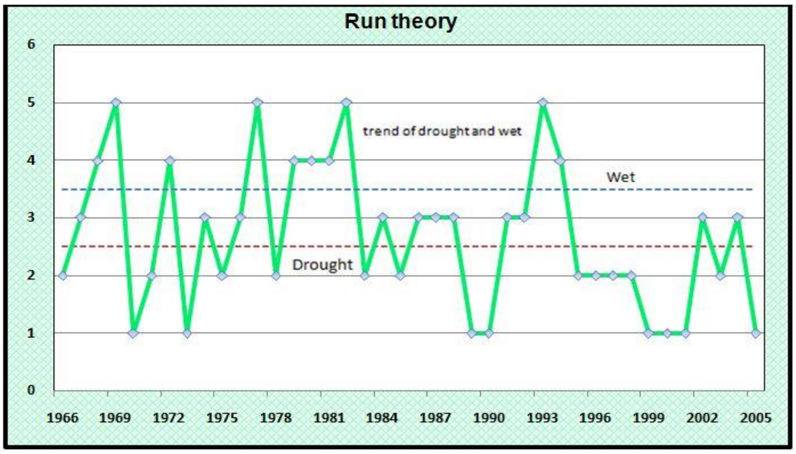

Fig. 5. Trend of wet and dry periods in Lake Urmia basin Using Runs theory

Table 9. Frequency distribution for first order transition counts

	VD	D	N	W	VW
VD	3	1	3	0	0
D	1	3	5	2	0
N	2	3	3	0	3
W	1	1	0	2	2
VW	1	2	0	1	0

Table 10. Annual transition probability matrix

	VD	D	N	W	VW
VD	0.43	0.14	0.43	0.00	0.00
D	0.09	0.273	0.455	0.182	0.00
N	0.182	0.273	0.273	0.09	0.182
W	0.167	0.167	0.00	0.333	0.333
VW	0.25	0.50	0.00	0.25	0.00

Table 11. Annual equilibrium probability

VD	D	N	W	VW
0.23	0.27	0.23	0.17	0.1

For Markov chain analysis, we assume that the rainfall in this year depends on the rainfall in the previous year. Therefore, Based on five categories of Runs theory (very dry, dry, normal, wet, and very wet), the frequency matrix is formed during 40 years (1996-2005) in Lake Urmia basin. The transition frequency from dry state to normal state is slightly larger than those from other states. The transition probability matrix represents the weather model in which the trend of the following year is estimated. Transition probability matrix of wet- dry spells is created accordingly based on maximum likelihood method (Table 10).

To find the equilibrium probabilities we compute the n-step transition probabilities, which mean that for example the probability of dry periods occurrence regardless of the weather conditions of the previous year is 0.27 for Lake Urmia Basin. The equilibrium probabilities of very dry, normal, wet and very wet periods are 0.23, 0.23, 0.17 and 0.1, respectively.

5. Conclusions

This study focused on the application of four known drought indices (PNPI, SIAP, RAI ans SPI) for drought detection and monitoring in Lake Urmia Basin in Iran for 40 years (1966-2005). In most of the indices, the slight and moderate droughts are more frequent. Approximately every ten years, a severe drought takes place in the Lake Urmia basin. The results of SIAP, RAI and SPI are similar approximately, but they are different from PNPI. PNPI has not estimated any kind of extreme and severe drought that is far from the reality. It seems that PNPI is not an appropriate index in annual estimates and an increase in time period is an obstacle to PNPI estimates. RAI considers the extreme changes mostly and performs well in estimating the extreme drought and wet periods. Therefore, in areas with high rainfall variability, the anomaly index is better than other indices and its results are nearer to reality. The SPI method gives best result without other climatic parameters as it uses only precipitation data and gives accurate result.

Two probability approaches including Runs theory and Markov chain model, used to estimate the probability of wet and dry periods in Lake Urmia Basin. The frequency matrix is formed and the transition probability matrix of wet- dry spells is created accordingly based on maximum likelihood method. The equilibrium probability is calculated based on succeed power on probability matrix. The equilibrium probability of very dry, dry, normal, wet and very wet periods is obtained as 0.23, 0.27, 0.23, 0.17 and 0.1, respectively.

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