

Spatial Analysis of Meteorological Drought in Iran from 1965 to 2003

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Abstract

The present study examined year-to-year variations in areas affected by drought during a period of 39 water years in Iran. Ninety-five meteorological stations were chosen to provide near-continuous long-term records, although some data was missing (less than 10%). The missing data points were estimated using a linear correlation method between the reference station with the missing data points and a neighboring station that had a complete record. At all stations, the standard index of annual precipitation (SIAP) was calculated for water year (sum of precipitation from October 1 to September 31). The geo-statistical method of weighting moving average (WMA) was applied to a 2 × 2 km grid network map of Iran and the geographical distribution of SIAP was calculated and displayed. From this, the percentage of area affected by severe, moderate, and mild drought was computed for each year; the frequency of drought was analyzed by severity and the behaviors of the most extensive historical droughts were determined. The results showed that: a) the maximum frequency of severe drought was 5.1 times and moderate drought was 23.1 times per 100 years; b) the most extensive droughts (more than 80% of the country) occurred during 1970-1971 (82.21%), 1988-1989 (92.05%), and 1999-2000 (96.27%); and c) drought spread in Iran beginning from the northwestern and southeastern regions, gradually extending to the central regions.

Keywords: Drought; Severity; Extent; Geo-statistics; Iran

1. Introduction

Iran has an area of 1650 000 km² and is located in the semi-arid regions of Middle Asia at 25° to 40° north latitude and 44° to 64° east longitude. The latitudinal extension of the country affects its topography and the distance of some areas from the sea, producing diverse climates. An large part of Iran is arid (65%) or semi-arid (20%); the rest has Mediterranean to very humid climates (Khalili, 2004).

As do other countries located in arid and semi-arid regions, Iran faces a naturally dearth of precipitation in some years that becomes critical at times of severe drought. Although drought commonly occurs in Iran, its importance was highlighted after the devastating

droughts of 1998-2001, when the cost of the drought damage was estimated to be \$7.8 billion. Details of this drought have been described by Mousavi (Mousavi, 2002).

There are many definitions of drought, but none are universally accepted. Dracup *et al.* (1980) suggested categorizing drought and Wilhite and Glantz (1985) developed this into a system approved by the American Meteorological Society (AMS, 2000). Based on the nature of water shortage, drought can be classified as meteorological, hydrological, agricultural, or socio-economic. The first three categories are types of environmental drought and the last is related to water resource systems (Wilhite, 2000).

Meteorological drought is defined as a period of precipitation less than the long-term mean in a specific region and is the focus of the present study. Various indices are used to monitor meteorological drought. The most common are the Palmer drought severity index (PDSI);

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Palmer, 1965), Bahlme and Mooley drought index (BMDI; Bahlme and Mooley, 1980), standard index of annual precipitation (SIAP; JAMAB, 1991), standardized precipitation index (SPI; McKee *et al.*, 1993), effective drought index (EDI; Byun and Wilhite, 1999), and reconnaissance drought index (RDI; Tsakiris and Vangelis, 2005). Depending on the aim of the drought study, drought analysis may be done using single station (Yevjevich, 1967; Dracup *et al.*, 1980) or multi-station data (Santos *et al.*, 1983; Chang, 1991; Guttman *et al.*, 1992; Soule, 1992).

In the last decade, assessments of drought have been done on the national and regional levels in Iran. The results of two studies were used in this research. Bazrafshan (2002) compared seven meteorological drought indices for diverse climates in Iran (arid to very humid regions). He recommended SIAP, SPI, and EDI for drought monitoring on annual, monthly, and daily timescales, respectively. Akhtari *et al.*, (2009) compared the geo-statistical methods of kriging, co-kriging, thin plate smoothing spline, Theissen polygons, and WMA for spatial distribution of drought in Tehran province. Their results found that, although kriging is the most accurate method, WMA provided reasonable accuracy combined with simplicity and speed of procedure, and thus, can be also recommended for operational drought monitoring in the region.

The present study used SIAP to monitor meteorological drought in Iran and applied WMA to map SIAP across Iran for each year. The purpose of this research was to analyze the frequency and extent of drought and its spread across Iran over 39 years ending until 2003.

2. Methodology

2.1. Preliminary analysis of precipitation data

Precipitation sources in Iran can be divided into three general categories (Khalili, 2004): i) Mediterranean flows: a ridge of high-pressure build up over the Mediterranean Sea that moves east and enters the country from the southern and northern borders. This type affects the country for seven months from mid-October to mid-April; ii) northern Pacific Ocean flows: the build-up the northern Pacific Ocean crosses the Black Sea and enters the country from the northwestern borders; iii) Sudan flows: after crossing the Red Sea and the Persian Gulf, these

flows enter the country from the south and southwest and mostly affect southwestern regions. Besides these, there are two mid-scale sources for precipitation in Iran: i) advection precipitation: horizontal movement of a North Pole ridge over the Caspian Sea that affects coastal precipitation, especially in October and November; ii) India Ocean seasonal precipitation: India Ocean moisture flows enter Iran from the southeast in summer and affect those regions.

In this study, monthly precipitation data from 105 synoptic stations from 1951 to 2003 were collected throughout the country. Before using precipitation data in drought analysis, it was necessary to do the preliminary controls for the length of the homogeneous record period, and on missing data and its reconstruction. This was accomplished in the following steps:

- i. It was found that data from some precipitation records of the stations was missing for the statistical period of 1951-2003. Figure 1 shows the number of stations at which precipitation was measured for water years for 1951-2003. Water year precipitation is the sum of precipitation from October 1 of a given year to September 31 of the next year. As shown in Figure 1, there was a jump in the number of stations between 1963-64 (40 stations) and 1964-65 (100 stations). To accommodate this jump, the record period chosen for the study covered the water years 1964-65 to 2002-03.
- ii. After the basic length of the record was chosen, the frequency of missing data at each station was identified (Figure 2). It was found that 19 stations had no missing data and the amount of missing data at other stations ranged from 1 to 21 years. To ensure the suitability of the stations, those with more than 10% (4 years) missing data were omitted from the network. A total of 95 synoptic stations were chosen; Figure 3 shows the station network with over 35 years of records in the country.

There are various techniques to complete missing data at meteorological stations. In this study, the missing data was reconstructed using the linear correlation between each reference station with missing data and a suitable nearest neighbor station with complete data. The most suitable station was that which had the highest correlation with a reference station for the period for which both stations had recorded data.

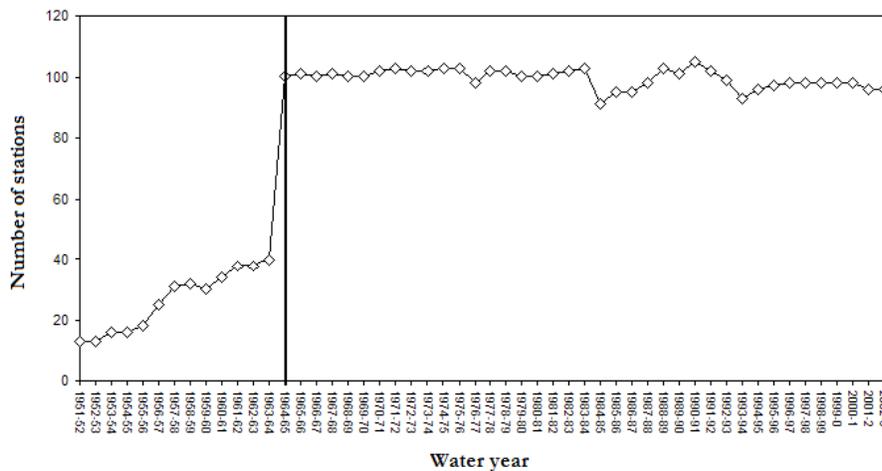


Fig. 1. Number of stations in which precipitation amount was measured, vs. water year during 1951-2003

2.2. Drought monitoring

SIAP was chosen for use as the drought index because: i) it is computationally simple and the only input required is annual precipitation, which is measured at most meteorological stations; ii) for meteorological studies performed by the Iranian Water Project (JAMAB, 1991), different thresholds were tested for SIAP that indicated that the thresholds

shown in Table 1 accurately detected historical drought in Iran. The equation for SIAP is:

$$SIAP_i = \frac{P_i - \bar{P}}{SD} \tag{1}$$

where P_i is the sum of precipitation in a given water year, \bar{P} is the average water year precipitation, and SD is the standard deviation of the water year precipitation (mm).

Table 1. Drought class classification of SIAP (JAMAB, 1991)

Drought classes	SIAP values
Normal and above normal	SIAP > -0.5
Mild drought	-1.0 < SIAP ≤ -0.5
Moderate drought	-2.0 < SIAP ≤ -1.0
Severe drought	SIAP ≤ -2.0

2.3. Interpolation technique for spatial analysis of drought

Geo-statistical techniques are frequently used for spatial analysis of environmental factors. One well-known methods is WMA, which served as the interpolation tool for spatial analysis of drought in this study. WMA was directly applied to SIAP values. In this technique, the quantity of a variable at an unknown point was estimated by adjacent known points using the following formula:

$$Z^* = \frac{\sum_{i=1}^k \frac{Z_i}{d_i^n}}{\sum_{i=1}^k \frac{1}{d_i^n}} \tag{2}$$

where Z^* is the estimated quantity at an unknown point, Z_i is the quantity of the variable at an adjacent point, d_i is the Euclidean distance between the Z_i to the Z^* , n is the power, and k is the number of adjacent points. As described by

Akhtari *et al.*, (2009), the optimal values for n and k were determined to be 2 and 6, respectively.

3. Results and Discussion

3.1. On-site analysis of drought

The SIAP calculations were done using the water year precipitation data from 1965 to 2003 from 95 synoptic weather stations. Figure 4 shows the maximum and minimum SIAP values in the country during the recording period. As seen, the range of SIAP across the country and for all water years varied from -2.51 (1996-97 at station 40752) to +4.84 (1971-72 at station 40753). Both stations are located in the province of Tehran. As shown, regardless of time and location, the most severe wet period was

approximately twice as large as the most severe dry period.

Knowing the relative frequency of drought, particularly extreme drought, is important when planning drought mitigation measures in a region. It is expected that the severe drought will occur less frequently than do other drought classes. Figure 5 shows the geographical distribution of drought frequency for severe, moderate, and mild drought and normal conditions for SIAP in Iran. As shown in Figure 5(d), the frequency of severe drought was less than 5.1 times per 100 years. The occurrence of severe drought in the provinces of Greater

Khorasan, Kerman, and West Azarbaijan was greater than for the other provinces. Moderate and mild drought occurred 23.1 and 33.3 times per 100 years, respectively. Figure 5(c) shows that the occurrence of moderate drought in the northern half of Greater Khorasan, in other northwestern and western provinces, and in some southern areas was greater than for other regions. Figure 5(b) shows that the frequency of mild drought was highest in provinces running diagonally southeast-northwest, along the southern coasts, and in northern Greater Khorasan.

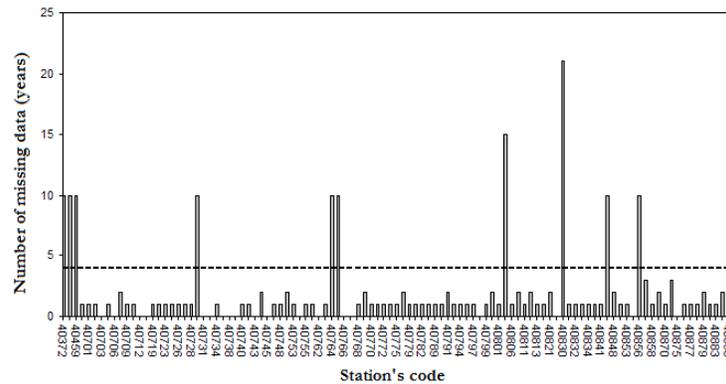


Fig. 2. Number of missing data in each station. The dashed line represents the threshold of acceptable missing data for reconstruction during record period

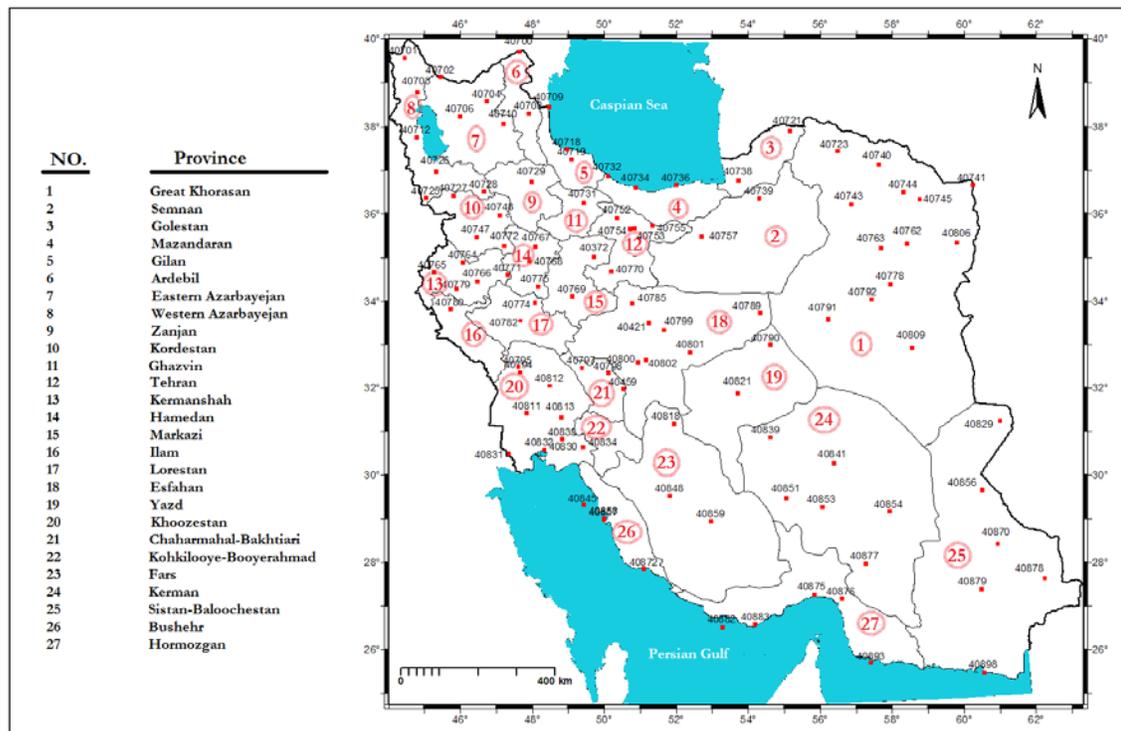


Fig. 3. The stations network for drought analysis

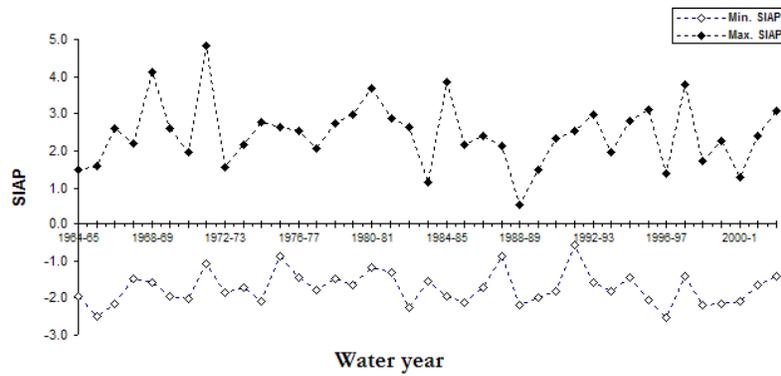


Fig. 4. The maximum and minimum quantity of SIAP in the country during the statistical period of 1965-2003

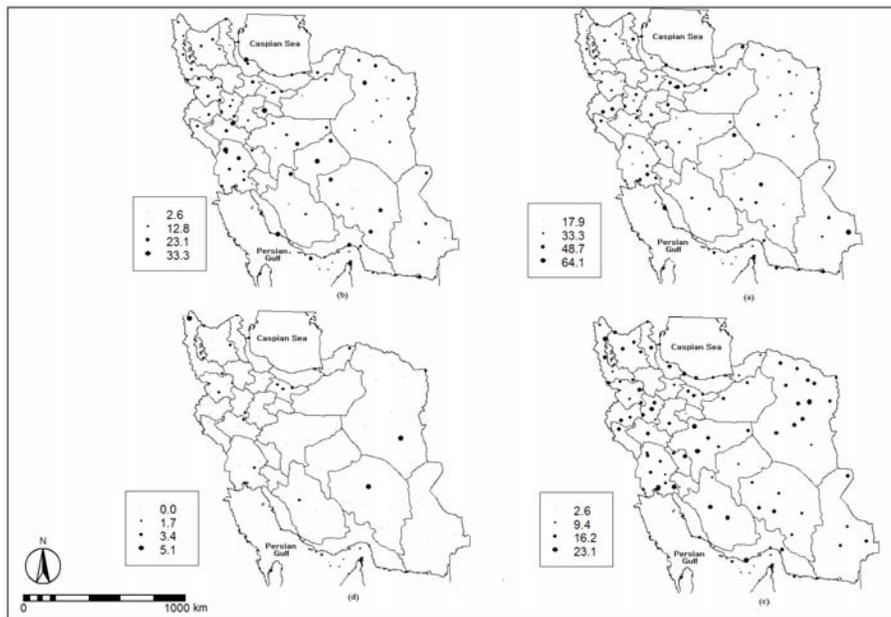


Fig. 5. Geographical distribution of drought frequency for severe, moderate, and mild categories along with normal category of SIAP in Iran

3.2. Spatial analysis of drought

WMA (ILWIS software, ver.3.0 environment) was used on the SIAP values computed at the stations of interest, maps of the iso-SIAP values were drawn, and the areas for the drought categories were computed for each water year. The areas affected by both drought and wet periods by water year are shown in Table 2. Except for water year 1999-2000, in which severe drought affected 0.11% of the country, severe drought was experienced by less than 0.02% of the rest of the country; however, for 80% of water years, the country did not experience severe drought. In 1999-2000, more than 70% of the country experienced moderate

drought that was almost twice the extent of moderate drought in other water years.

The most extensive droughts in Iran (>80% of country) occurred during 1970-1971 (82.21%), 1988-89 (92.05%), and 1999-2000 (96.27%). The latter was the most extensive and intensive drought occurring in the statistical period of interest. It is evident that the extent of drought in Iran increased from 1965 to 2003 and the time interval between extensive droughts decreased from 20 years (1970-1971 to 1988-1989) to 10 years (1988-1989 to 1999-2000). Figures 6, 7, and 8 show the periods during which the 1970-1971, 1988-1989, and 1999-2000 droughts developed, respectively.

Table 2. Distribution of country's area (in terms of percent) in different classes of SIAP

Water year	Drought			Normal	Wet period		
	Severe	Moderate	Mild		Mild	Moderate	Severe
1964-65	0	10.3	29.63	56.83	3.18	0.15	0
1965-66	0.09	19.96	46.88	32.14	0.9	0.03	0
1966-67	0	8.84	48.95	36.19	5.58	0.43	0.02
1967-68	0	0.06	1.54	89.36	8.19	0.84	0
1968-69	0	0.98	1.96	33.83	27.14	27.06	9.04
1969-70	0	7.08	55.87	33.12	3.18	0.71	0.04
1970-71	0	40.82	41.39	17.74	0.04	0.01	0
1971-72	0	0	0.01	15.33	37.83	44.95	1.88
1972-73	0	34.05	38.3	27.02	0.6	0.04	0
1973-74	0	0.24	9.29	77.73	12.02	0.72	0.01
1974-75	0	4.86	19.96	64.36	4.89	5.05	0.89
1975-76	0	0	0	14.75	34.73	50.39	0.13
1976-77	0	0.04	7	76.02	15.03	1.9	0.01
1977-78	0	0.08	4.47	85.19	9.69	0.57	0
1978-79	0	0.09	4.68	68.56	20.38	6.23	0.06
1979-80	0	0.21	1.41	65.83	22.07	10.42	0.06
1980-81	0	0.01	8.84	69.01	16.77	4.98	0.39
1981-82	0	0.07	7.05	61.85	15.5	13.09	2.45
1982-83	0.02	0.91	1.11	31.03	42.28	24.61	0.04
1983-84	0	7.98	35.68	56.09	0.24	0	0
1984-85	0	3.93	46.13	48.71	1.06	0.14	0.02
1985-86	0	0.36	17.05	63.87	16	2.72	0
1986-87	0	0.96	9.16	73.98	12.52	3.34	0.04
1987-88	0	0	0.43	58.09	25.88	15.61	0
1988-89	0	31.37	60.68	7.94	0	0	0
1989-90	0	3.91	32.84	56.21	6.14	0.9	0
1990-91	0	1.83	18.13	44.78	25.03	10.19	0.05
1991-92	0	0	0.01	38.32	41.6	20.05	0.03
1992-93	0	0	0.07	28.31	33.64	35.1	2.87
1993-94	0	10.65	47.78	31.65	8.21	1.71	0
1994-95	0	0.03	3.95	42.49	30.73	22.62	0.18
1995-96	0	1.57	3.12	29.36	16.65	30.25	19.05
1996-97	0.01	12.42	39.6	42.82	3.96	1.18	0
1997-98	0	0.13	3.37	31.65	25.22	34.36	5.28
1998-99	0	16.72	16.33	62.28	4.32	0.35	0
1999-00	0.11	73.21	22.95	3.69	0.04	0.01	0
2000-01	0.01	39.42	32.22	28.27	0.08	0	0
2001-02	0	11.54	14.06	63.51	8.04	2.84	0.01
2002-03	0	1.11	28.07	53.51	13.1	4.17	0.04

3.2.1. 1970-1971 drought

The occurrence of drought in water year 1968-1969 was the starting point of the widespread drought of 1970-1971. Figure 6(a) shows that this drought commenced in a small area from the southeast corner of the country and the following year (Figure 6(b)) encompassed southwestern, central, northeastern and western regions of the country. Continued lack of precipitation increased the severity and extent of drought in 1970-1971 (Figure 6(c)) over that of the previous year. Except for those western, central and southeastern parts of the country, mild and moderate drought dominated. Note that the following year (1971-1972), normal and above normal precipitation conditions occurred across the country (Figure 6(d)); although it appears

that, in water year 1971-1972, the widespread drought from the previous year terminated, in 1972-1973, large parts of the country (southern Alborz Mountains) again experienced drought.

3.2.2. 1988-1989 drought

The mode of formation of extensive drought in 1988-1989 differed from the 1970-1971 drought. Figures 7(a) to 7(d) show drought conditions before the drought of 1988-1989. It can be observed that there was relatively widespread drought from 1984-1985 (Figure 7(a)) until 1987-1988, when it gradually receded. In 1987-1988, normal and above-normal conditions dominated the country; however, in 1988-1989, nearly the entire country unexpectedly experienced drought (Figure 7(e)).

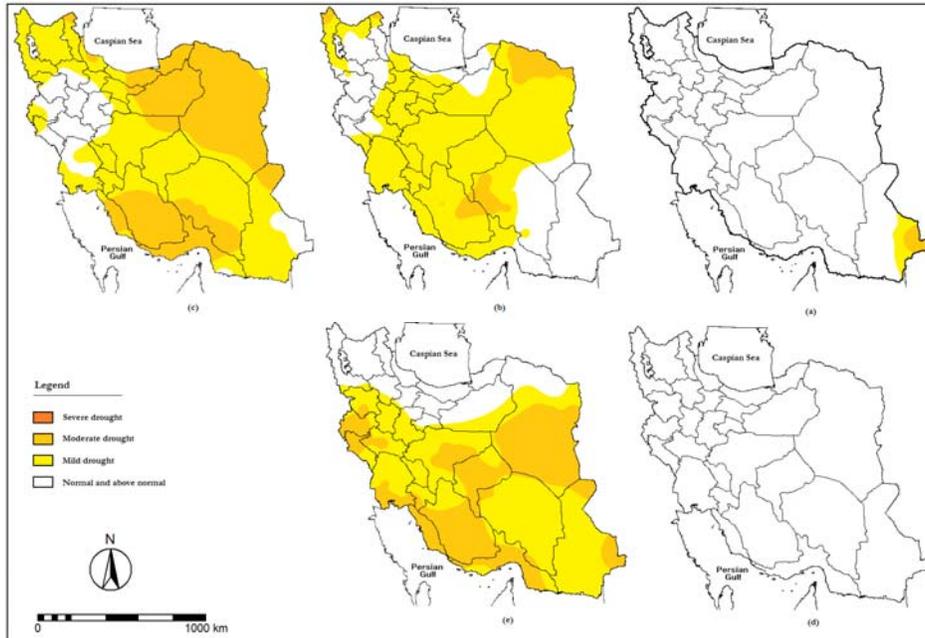


Fig. 6. Spatial distribution of SIAP drought classes over Iran: a) 1968-1969, b) 1969-1970, c) 1970-1971, d) 1971-1972, and e) 1972-1973

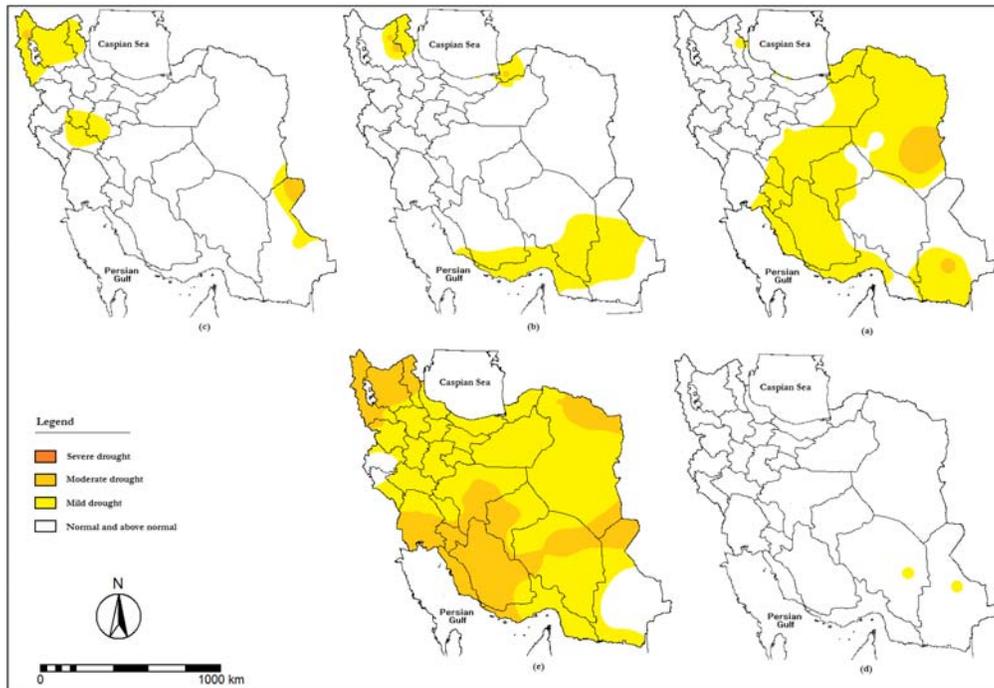


Fig. 7. Spatial distribution of SIAP drought classes over Iran: a) 1984-1985, b) 1985-1986, c) 1986-1987, d) 1987-1988, and e) 1988-1989

3.2.3. 1999-2000 drought

Figures 8(a) to 8(d) show the movement of drought over the country before the occurrence of extensive drought in water year 1999-2000. Figure 8(a) shows that a drought entered the

country from the northwest and northeast in water year 1995-1996. The following year, its range expanded to central parts of the country from west to east (Figure 8(b)). If this trend had continued during the following year (Figure 8(c)), the country would have faced serious

crisis; this did not occur and the area of drought receded toward the northeastern borders of the country. The drought map for the following year (Figure 8(d)) indicated that, once again, the drought developed from the northwest toward

the central regions. This trend continued in water year 1999-2000 and the most devastating drought in the preceding 40 years (up until 2003) was triggered (Figure 8(e)).

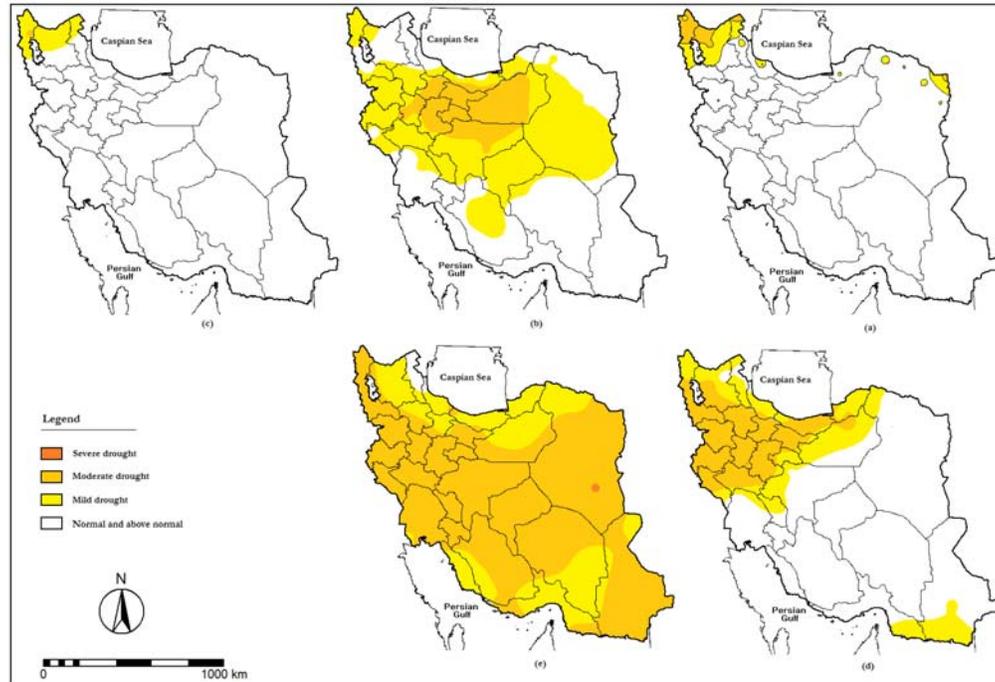


Fig. 8. Spatial distribution of SIAP drought classes over Iran: a) 1995-1996, b) 1996-1997, c) 1997-1998, d) 1998-1999, and e) 1999-2000

4. Conclusion

In this research, the severity and extent of droughts in Iran from 1965 to 2003 were analyzed. Drought monitoring at each station used SIAP drought index. The SIAP values in Iran varied from -2.51 to +4.84. At most stations, maximum positive SIAP values show a severe wet period and minimum negative SIAP values show moderate drought conditions. Assessing the frequency for each SIAP class indicates that severe and moderate drought occurred less than 5.1% and 23.1% of the time during the statistical period of interest. The geo-statistical WMA method was used to map SIAP across the country. The most extensive droughts in Iran (>80% of the country) occurred during 1970-1971 (82.21%), 1988-1989 (92.05%), and 1999-2000 (96.27%). It is evident that the extent of drought in Iran increased from 1965 to 2003 and that the time interval between pervasive droughts decreased.

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