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Remote sensing-based monitoring of the spatiotemporal characteristics of drought using hydro-meteorological indices

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ABSTRACT

Due to climate change, drought events will probably occur more frequently and be more intense. Therefore, effective drought monitoring and assessment is vital in developing knowledge of drought, drought adaptation, and mitigatory actions. Remote sensing has been widely used for monitoring drought in recent years. In the current research, three groups of remote sensing indices, i.e. vegetation, thermal and moisture indices, were applied to determine the correlation between them and the standardized precipitation index (SPI) as drought index for the growing season (April to September) from 1999 to 2005 for rangeland areas in the Alborz province of Iran. The results indicated that normalized difference vegetation index (NDVI) (with a correlation coefficient of 0.74) and land surface temperature (LST) (with a correlation coefficient of 0.67) had the highest correlations with rainfall. Therefore, it concluded that the assumed indices are suitable for drought monitoring for this land use. Temporal analysis of the results showed that the best correlations of remote sensing indices belonged to the 6- and 9-month SPI and indicated the effect of long-term rainfall on plant growth.

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Introduction

Drought is known to be a recurrent natural phenomenon that occurs at multiple time scales and affects many regions around the world (Below et al., 2007; Van Loon et al., 2016). Simply, drought is a complex natural phenomenon that arises from a reduction in rainfall over an extended period, which causes an insufficient amount of moisture to be stored in the soil (Abbaspour and Sabetraftar, 2005; Mishra and Singh, 2010; Vurukonda et al., 2016; Kaisermann et al., 2017). Due to climate change and global warming, droughts have been observed more frequently and have been more severe in recent years, especially in arid and semi-arid regions. Alborz province is one of the most important agricultural and industrial provinces in northern Iran, and since the late 1990s, it has been affected by drought (Bazrafshan and Khalili, 2013). Increased frequency and severity of drought have had a significant impact on water resources, agricultural production, and consequently the economy across Alborz Province. Therefore, drought monitoring, assessment, and management are vital for decision makers.

Many drought indices are applied to effectively monitor and assessment drought, including the moisture index (MI) (Thornthwaite et al., 1955), Palmer Drought Severity Index (PDSI) (Palmer, 1965) and the Standardized Precipitation Evapotranspiration Index (SPEI) (Vicente-Serrano et al., 2010). Two important meteorological and hydrological indices, i.e. the Standardized Precipitation Index (SPI) (McKee et al., 1993) and the Standard Water Level Index (SWI) have also been used in many previous studies and were successful in quantifying the severity of short- and long-term drought for a given location and time (Guhathakurta et al., 2017; Halder et al., 2020). Because drought is a regional event, it should be monitored and evaluated on both a time and a space scale (Kogan 1997; Anderson et al., 2011; Hao et al., 2015). Remote sensing techniques are efficient and practical methods that can be applied to monitor drought in space (Toth and Jóźków, 2016). Remote sensing provides satellite observations over large regions at different temporal intervals. It systematically and continuously provides information (such as vegetation) and resolve the shortcomings of in-situ data for drought indices (Xu et al., 2018).

In recent years, different indices derived from remote sensing data, including vegetation, thermal, soil moisture, hydrological and meteorological ones have been applied to monitor and assess drought severity (AghaKouchak et al., 2015, Liu et al., 2020). Some popular remote sensing drought indices which are also useful for drought monitoring include the Normalized Difference Water Index (NDWI), Normalized Difference Vegetation Index (NDVI), Vegetation Condition Index (VCI), Vegetation Health Index (VHI), Anomaly of Normalized Difference Vegetation Index (NDVIA), Soil Wetness Deficit Index (SWDI), Land Surface Temperature (LST), Temperature Vegetation Dryness Index (TVDI), and Temperature Condition Index (TCI) (Kogan, 1995; Rhee et al.2010; Zargar et al., 2011; Zhang and Jia, 2013; Hao and Singh, 2015; Guo et al., 2018)..

Drought events occur for a variety of reasons; thus, many composite drought indices have been developed to monitor and evaluate drought by combining remote sensing drought indices, such as SMCI, VCI, PCI, TCI, etc. Some common composite drought indices are presented in Table 1. Martinez-Fernandez et al., (2016) assessed the SWDI index in monitoring agricultural drought and compared it with other indices, including the Crop Moisture Index and Atmospheric Water Deficit. Zhang et al., (2017) discussed multi-sensor frameworks and indices and assessed their ability to determine agricultural drought. Sanchez et al., (2018) evaluated the use of different remote sensing indices to predict agricultural drought. They reported that using remote sensing indices could provide appropriate results; however, using soil moisture indices can improve the results significantly. Six different meteorological indices for monitoring agricultural drought in the south-central USA were studied by Tian et al., (2018) and Hu et al., (2020) applied land surface temperature indices to monitor agricultural drought severity. Many combined drought indices have also been suggested, such as the scaled drought condition index (SDCI) (Rhee et al., 2010) the synthesized drought index (SDI) (Du et al., 2013), optimized drought indices (ODIs) (Hao et al., 2015), and the process-based accumulated drought index (PADI) (Zhang et al., 2017).

It is noteworthy that the effectiveness of these drought indices depends on regional drought monitoring, and many of them may not adequately detect the roles of single factors in the drought occurrence. Therefore, the current research applied the Pearson correlation coefficient method to compare some remote sensing indices with SPI drought index and to analyze the drought in Alborz province.

The main purposes of the current research were to evaluate the capability of single remote sensing indices in monitoring and assessing drought and to compare the correlation coefficients of remote sensing indices with SPI in monitoring meteorological drought in the Alborz province over space and time.

Table 1. Summary of some composite drought indices

Composite index	Data sources	Method	Reference
SDCI	Precipitation, LST, NDVI, reflectance	Empirical weights	(Rhee et al., 2010)
MIDI	Precipitation, soil moisture, and LST	Empirical weights	(Zhang and Jia, 2013)
SDI	Precipitation, LST and NDVI	Principal Component Analysis (PCA)	(Du et al., 2013)
MDI	Precipitation, runoff, evapotranspiration and soil moisture	Kernel PCA and kernel entropy component analysis (KECA)	(Rajsekhar et al., 2015)
OMDI/MVDI	Precipitation, soil moisture, LST and NDVI	Empirical weights, PCA, and constrained optimization	(Hao et al., 2015)
PADI	Precipitation, soil moisture, NDVI	Evolution Process-based Multi-sensor Collaboration (EPMC)	(Zhang et al., 2017)
MCDI	Precipitation, LST and NDVI	Multivariable Linear Regression	(Liu et al., 2020)

Materials and Methods

Study Area

The study area is Alborz province where located in the northern part of Iran over a longitude of 50°9' to 51°28' and latitude of 35°32' to 36°20', covering a total area of 5833 km^2 (Fig. 1). Annual average precipitation in Alborz is about 361 mm, and winter and summer have the highest and lowest amounts of annual precipitation with 42.3% and 5.1%, respectively. The climate of Alborz province is highly diverse, exhibiting desert climes in the southern parts and semi-humid and humid climes in the northern parts. Considering the general situation of the province, the most serious conflicts of the north-south climate are seen in the south of the province (Moazami, 2016; Pishgar-Komleh et al., 2017; Omid et al., 2018).

In recent years, Alborz province has had to cope with less precipitation and unsuitable distribution, and the frequent and severe drought events have brought about significant restrictions in production in its agricultural and rangeland regions. Thus, this study considered rangeland areas, the most common land use in Alborz province, as the most important priority in the study of drought monitoring and assessment. To this end, the study area classified into the four categories including rangeland and the other land uses (Fig. 2).

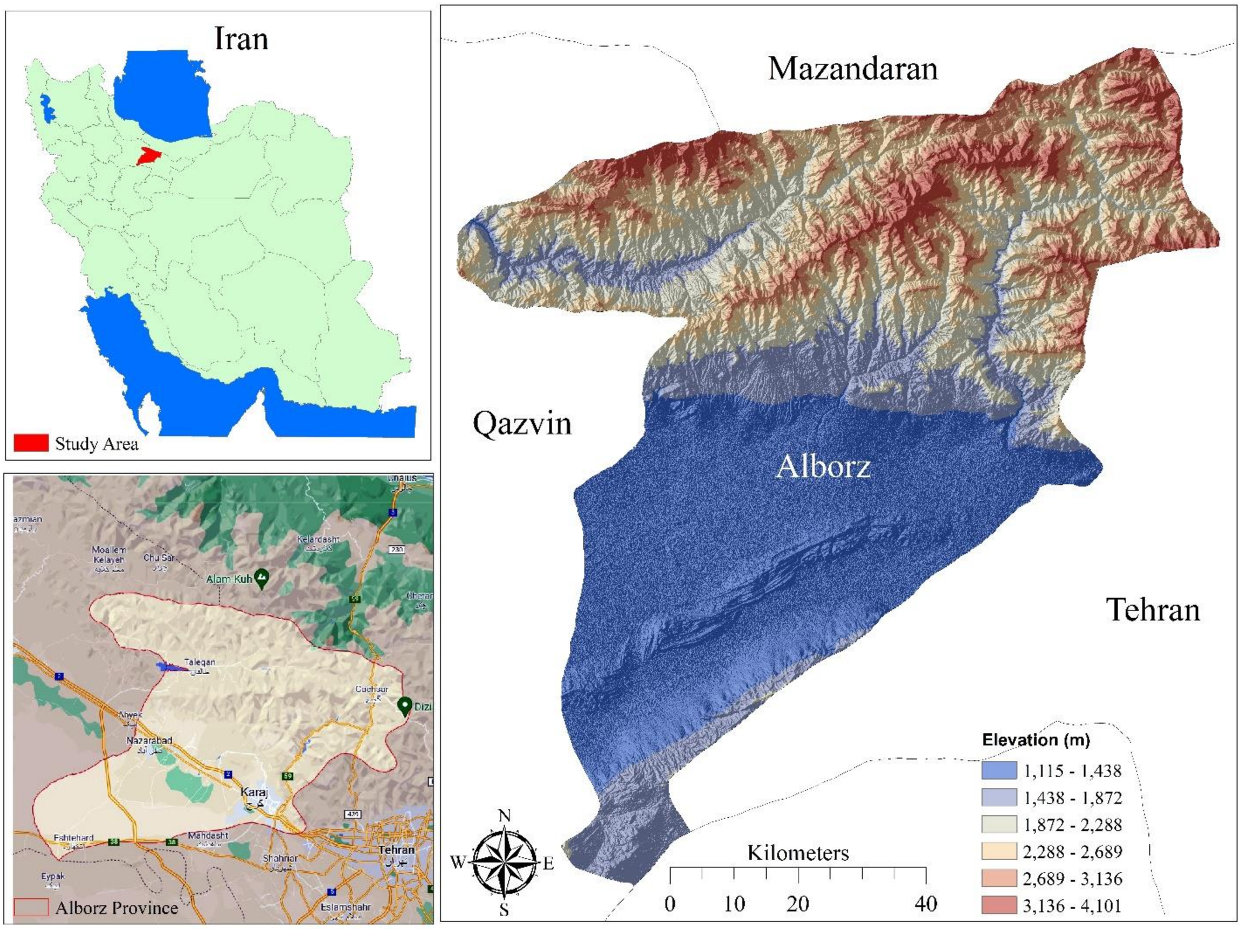

Figure 1. Geographical location and elevation model of the study area

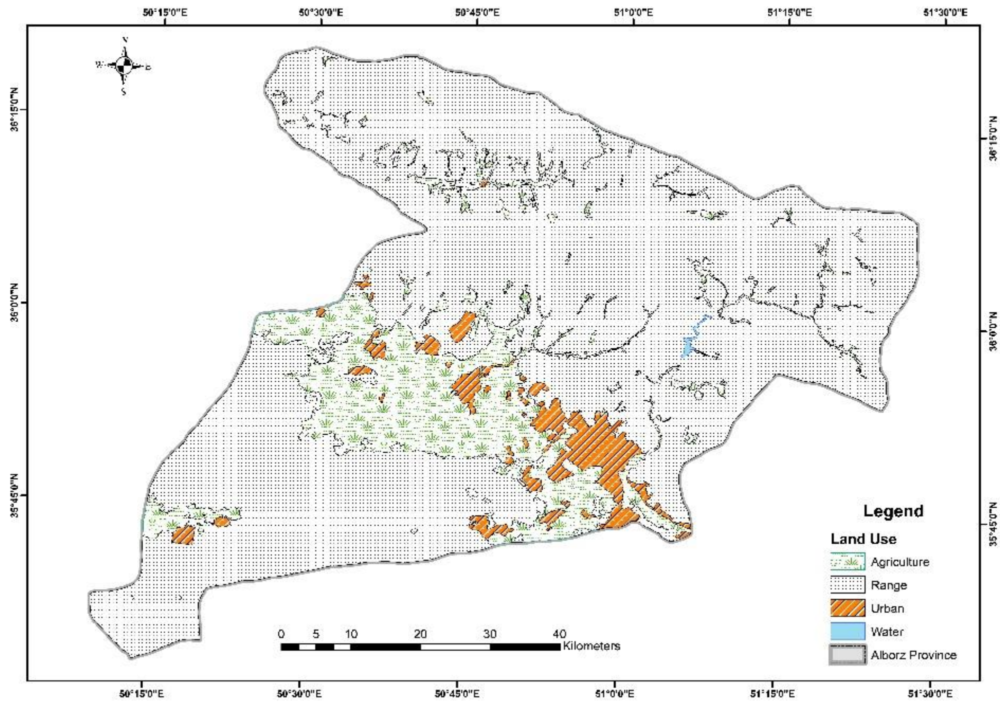

Figure 2. Classification of the study area based on land use

Satellite Data

In current research cloud free and corrected atmospheric/radiometric (L2T) satellite images of Landsat-5 TM (Thematic Mapper) with 30 m resolution were freely obtained from the United State Geological Survey (USGS; https://earthexplorer.usgs.gov). The TM data (path/row:165/35) was collected for the months of April to September during the period 1999-2005. These months was selected, because the peak growth of vegetation occurs during these times of year in the northern hemisphere (Kong et al., 2017). All the acquired images were projected in UTM Zone 39 N (WGS 84) and all scenes were verified for geometric accuracy. In this study, the satellite data were used to create different kind of spectral indices. Accordingly, in order to detect and monitor drought timely at study area, we investigated three groups of satellite indices: (a) vegetation, (b) thermal, and (c) soil moisture indices.

Vegetation Indices

In the current study, the applied vegetation indices included Normalized Difference Vegetation Index (NDVI), Vegetation Condition Index (VCI), Vegetation Health Index (VHI), Normalized Difference Water Index (NDWI), and Normalized Difference Vegetation Index Anomaly (NDVIA). The NDVI is the most popular vegetable index and has been used to monitor drought severity in different regions (Duan et al., 2017). The VCI index was determined based on the maximum and minimum NDVI values during the study period (Zambrano et al., 2016). The VHI index reflects the vegetation health status and is calculated based on the values of the VCI and TCI indices for the given time (He et al., 2018). The NDWI index shows the water content and determines the moisture stress level of the plant. This index can be calculated using near infrared (NIR) and infrared short wave (SWIR) bands (Donia et al., 2019). The NDVIA index expresses the difference between the NDVI values and its average value over a given period (Li et al., 2016). Table 2 shows the equation used to calculate these indices.

Table 2. Relation for the Vegetation Indices

Index	Relation	Reference
NDVI	$NDVI = \frac{\rho_{NIR} - \rho_{RED}}{\rho_{NIR} + \rho_{RED}}$	Ji and Peters (2003); Nouri et al. (2017)
VCI	$VCI = \frac{NDVI_{ijk} - NDVI_{i\,min}}{NDVI_{i\,max} - NDVI_{i\,min}}$	Kogan (1995, 2001)
VHI	$VHI = r_1 \times VCI_{ijk} + r_2 \times TCI_{ijk}$	Gao (1996)
NDWI	$NDWI = \frac{\rho_{NIR} - \rho_{SWIR}}{\rho_{NIR} + \rho_{SWIR}}$	Gao (1996)
NDVIA	$NDVIA = \overline{NDVI_{ij}} - NDVI_{ijk}$	Anyamba et al (2001)

Where ρ_{RED} is the reflection of the red spectrum. ρ_{NIR} and ρ_{SWIR} show the reflections near infrared spectrum and near short-wave infrared spectrum, respectively. $NDVI_{ijk}$ is the monthly $NDVI$ value for pixel i in month j and year k. $NDVI_{i\,max}$ and $NDVI_{i\,min}$ are the maximum and minimum values of the multi-year NDVI for pixel i, respectively. VCI_{ijk} and TCI_{ijk} are the monthly VCI and TCI values for pixels i in month j and year k, respectively. r_1 and r_2 are the weights of VCI and TCI (in the most similar researches, they were considered to be 0.5). $\overline{NDVI_{ij}}$ is the average value of the NDVI index for pixel i in month j.

Thermal Indices

This research used the two thermal indices of land surface temperature (LST) and temperature confidence index (TCI). From among the different methods for calculating LST using thermal infra-red data, this study used a single-band method. To determine the LST, the brightness temperature must be calculated. Thus, the thermal infrared data must first be converted into radiation using Planck law (Zare et al., 2020).

$$T_b = \frac{k_2}{\ln(\frac{k_1}{l\lambda}+1)} \tag{1}$$

Where T_b is the brightness temperature, $l\lambda$ is the spectral radiation in $Wm^{-2}\mu m^{-1}sr^{-1}$, and k_1 and k_2 are the calibration coefficients with dimension $Wm^{-2}\mu m^{-1}sr^{-1}$.
Calculating the TCI also needs the brightness temperature. High temperature or low TCI indicates drought severity. Due to the fact that increasing in surface temperature is earlier than vegetation decline during drought periods, it seems that this group of indices is useful for assessing the drought severity in plant-covered areas (Shao-E et al. 2010). Table 3 illustrates the equation for calculating these indices.

Table 3. Relations for the Thermal Indices.

Index	Relation	Reference
LST	$LST = \frac{T_b}{[1 + \left(\frac{\lambda T_b}{\alpha}\right) \ln \varepsilon]}$	Artis and Carnahan (1982)
TCI	$TCI_{ijk} = \frac{(BT_{ijk} - BT_{i\,min})}{(BT_{i\,max} - BT_{i\,min})}$	Kogan (1995, 2001)

Where LST is the surface temperature, T_b is the brightness temperature, λ is the wavelength of the radiation, ε is the radiation power and $\alpha = hc/k$ (h is the Planck's constant, c is the speed of light and k is the Boltzmann's constant). BT_{ijk} is the brightness temperature for pixel i in month j and year k, $BT_{i\,max}$ and $BT_{i\,min}$ are the maximum and minimum brightness temperatures for pixel i in a particular period.

Soil Moisture Indices

This study used the two common soil moisture indices of soil wetness deficit index (SWDI) and temperature-vegetation dryness index (TVDI). These indices show the relationship between soil temperature, vegetation and soil moisture in a range between zero and one. The SWDI index has a direct correlation with soil moisture, but the TVDI index indicates an inverse relationship (Sayago et al., 2017). Table 4 shows the equation for these indices.

Table 4. Relations for the Soil Moisture Indices

Index	Relation	Reference
SWDI	$SWDI = \frac{T_{\max(i)} - T_{s(i)}}{T_{\max(i)} - T_{min(i)}}$	Verstraeten (2006); Mallick et al. (2009)
TVDI	$TVDI = \frac{LST - LST_{min}}{LST_{max} - LST_{min}}$	Sandholt et al. (2002)

Where i is the pixel number, $T_{s(i)}$ is same as the LST for pixel i, $T_{min(i)}$ and $T_{\max(i)}$ are the minimum and maximum observed temperatures for pixel i, respectively.

Meteorological data

Data on daily precipitation from 1973 to 2013 for the study area were obtained from the Iran Meteorological Organization, and no data was missing for the study area. There are 33 weather stations in Alborz province.

The SPI index was presented in 1993 by McKee et al., (1993). It was designed to quantify precipitation deficit at multiple time scales. The SPI index is calculated using Equation 2.

$$SPI = \frac{p_i - \bar{p}}{SD} \quad (2)$$

Where $p_i$the rainfall amount is during the desired period at the i^th^ station, $\bar{p}$ is the average rainfall at the i^{th} station and SD is the standard deviation of the i^{th} station's rainfall. Long-term rainfall data (over 30 years) must be used to calculate the SPI. Thus, the meteorological data (including daily and monthly rainfall) was collected from three synoptic stations and 30 rain-gauge stations in the study area. Some stations, however, had been established less than 30 years ago. Therefore, only 10 rain-gauge stations with sufficient data were selected for data collection, and the SPI indices for the periods of 1, 3, 6, 9, 12, and 24 months were calculated for the years 1973 to 2013. Moreover, annual SPI indices were calculated to determine the driest and wettest years.

Data analysis

The relationships between data can be investigated in different ways. One method is correlation analysis. Generally, correlation analysis determines type and severity between two sets of data. In the popular Pearson correlation analysis, the result is declared as a correlation coefficient named r, the value of which is between –1 to +1, such that 0 means there is no correlation between data. Positive values indicate a direct correlation between data, and negative values indicate an indirect correlation (Rahimzadeh Bajgiran et al., 2008).

After the data collection process, the correlation between remote sensing indices and meteorological drought index were calculated, and the results were analyzed for rangeland area. The best index and the best time scale for drought monitoring were determined, and then drought zoning maps were represented using the Kriging method (Kleijnen, 2017).

Results and Discussion

Correlations between SPI and remote sensing indices

The remote sensing index values were calculated based on weather station locations during the research period. To evaluate the efficiency of single remote sensing indices in drought monitoring and assessment, the correlation coefficients (r) were computed between each single remote sensing drought index and the SPI in the study area.

According to the annual SPI values, the driest and wettest years were identified as 2000 and 2005, respectively. Thus, the correlation coefficients were calculated between SPIs and remote sensing indices for these years for rangelands. The results for the driest year are shown in Table 5.

Table 5 indicates that NDVI (r=0.74) and TCI (r=-0.79) indicated the highest r with SPI-12 in rangeland areas. TCI was the most sensitive in monitoring long-term drought compared with other remote sensing indices, and again the r decreased as the SPI time scale decreased. Results showed that for the SPI short-time scale, TCI and NDWI had the highest r with SPI-3 compared to other indices in rangeland areas. This suggests that TCI and NDWI are able to provide valid and considerable but time-lagged information in meteorological and vegetation drought monitoring and assessment. For SPI-1, the results showed that VCI and VHI had the highest r in rangeland areas. The results also indicated that NDVIA showed the highest r with SPI-24 compared to other SPI time scales in both types of land use. LST showed the highest r with SPI-24 in rangeland areas. The values of r between NDWI and LST in rangeland areas were lower than those between other remote sensing indices and SPIs. NDWI and SPI-12 and LST and SPI-6 showed higher r values than between NDWI, LST and other SPIs, which suggests that the drought information reflected in NDWI was lagged for a longer time than in LST. The results for the wettest year are shown in Table 6.

Table 5. Correlation between different time scale SPIs and single remote sensing indices for rangelands in the study area for the driest year (2000)

		SPI1	SPI3	SPI6	SPI9	SPI12	SPI24
Rangelands	NDVI	0.2987	0.1332	0.3856	0.7021	0.7419	0.5222
	VCI	-0.4274	0.0794	-0.1262	-0.4220	-0.5086	-0.3984
	VHI	-0.4083	-0.1522	-0.3664	-0.5875	-0.6495	-0.5174
	NDWI	-0.0020	-0.3228	-0.3890	0.3746	0.5232	0.3371
	NDVIA	-0.0500	-0.1676	-0.0510	-0.0360	-0.1742	-0.3324
	LST	-0.0421	-0.2909	-0.2214	-0.1582	-0.1179	-0.3424
	TCI	-0.2939	-0.4668	-0.6202	-0.6978	-0.7945	-0.5473
	SWDI	0.0417	0.2908	0.2210	0.1573	0.1169	0.3418
	TVDI	-0.0417	-0.2908	-0.2210	-0.1573	-0.1169	-0.3418

Table 6. Correlation between different time scale SPIs and single remote sensing indices for rangelands in the study area for the wettest year (2005)

		SPI1	SPI3	SPI6	SPI9	SPI12	SPI24
Rangelands	NDVI	-0.0870	-0.1701	0.0916	0.3266	0.2840	-0.0883
	VCI	-0.4671	-0.1959	-0.3244	-0.8724	-0.6236	-0.6504
	VHI	-0.4453	-0.2380	-0.4472	-0.7102	-0.7410	-0.5999
	NDWI	0.4288	0.0730	0.0732	0.2713	0.3148	0.3940
	NDVIA	0.3195	0.2224	0.2956	0.2431	0.3095	0.5009
	LST	-0.1670	-0.4824	-0.6761	-0.5299	-0.5291	-0.5532
	TCI	-0.1525	-0.2495	-0.5148	-0.6829	-0.6550	-0.1645
	SWDI	0.1670	0.4822	0.6753	0.5288	0.5280	0.5529
	TVDI	-0.1670	-0.4822	-0.6753	-0.5288	-0.5280	-0.5529

Table 6 shows that VHI (r=-0.74) and VCI (r=-0.87) showed the highest r with SPI-12 and SPI-9 in rangelands, which indicated that VHI was the most sensitive in monitoring long-term drought compared with other remote sensing indices. Moreover, the r decreased as the SPI time scale decreased. Among thermal indices, TCI (r=-0.68) showed the highest r with SPI-9 in rangeland areas. Among soil moisture indices, SWDI (r=0.67) and TVDI (r=-0.67) showed the highest r with SPI-6 in rangeland areas. The results indicated that for the SPI short-time scale, VCI and LST had the highest r with SPI-1 and SPI-3 compared to other indices in rangeland land use. For the long-time scale, VHI and VCI showed higher r values with both SPI-12 and SPI-24 in rangelands. The r values between NDWI and SPIs were lower than those between other remote sensing indices and SPIs. NDWI and SPI-1 and VHI and SPI-12 showed higher r values than those between NDWI, VHI, and other SPIs, which suggested that the drought information reflected in VHI was lagged for a longer time than that in NDWI. The NDWI index indicates the moisture content of the vegetation cover; therefore, lower NDWI values indicate moisture stress in vegetation. In 2005, when the amount of precipitation was higher, this index showed the best correlation with SPI. During droughts, increases in surface temperature occur earlier than vegetation loss. The results showed that in the driest year, increasing surface temperatures of the leaves can determine plant moisture stress and the start of drought periods well. This heat reaction occurs even when plants are well-grown. It seems that considering an index that can assess the earth surface temperature for drought monitoring will lead to better results. In the present study, the results showed that the TCI index can show drought severity well, because vegetation density is less in rangeland regions than in agricultural regions, and there are also gaps between plants. Generally, it can be said that dense vegetation decreases surface temperature, and consequently, areas with dense vegetation have lower surface temperatures (Remote Sensing of Energy Fluxes and Soil Moisture Content, edited by George P. Petropoulos, 2014, Taylor & Francis Group, NW, pp 233-245).

Temporal correlation between SPI and remote sensing indices

Figure 3 illustrates the correlation between SPI and remote sensing indices in rangeland areas. In general, remote sensing indices did not show a satisfactory correlation with SPI in rangeland areas except for NDVI. The results showed that the NDVI had the highest correlations with SPI-9 and 12. The LST index showed a satisfactory correlation with SPI in April and May.

Figure 3. Correlation between SPIs and remote sensing indices in rangelands for the driest year (2000)

Comparison of SPI Zoning with Remote Sensing Indices

Figure 4 showed that SPI for the driest year (2000) was negative, indicating greater drought severity. The results showed that most of the study area, except for the northeastern part, had low precipitation and was faced with drought. SPI zoning for June 2005 as the wettest year is shown in Figure 5. In the wettest year, most parts of the study area, except the east and south areas did not experience drought.

According to the SPI values for 2000, there was a shortage of precipitation and, consequently, a drought event in most areas of the study region except for the northeastern part. The NDWI showed normal conditions in all parts of the research area. The NDVIA and TCI indices did not correlate well with SPI, but LST showed temperature changes in different regions. Results for this index showed that the northeastern parts of the Alborz province had lower temperatures. Soil moisture indices showed strong correlations with SPI. In general, the LST, SWDI, and TVDI indices showed a significant correlation with SPI in 2000. Based on SPI values in the wettest year (2005), most areas did not experience drought events except those in the eastern parts. The NDVIA also showed normal conditions in almost all parts of the study area. Clearly, vegetation and soil moisture indices were well correlated with SPI in the wettest year.

Conclusion

In the current research, the ability of remote sensing single drought indices to monitor and detect spatial and temporal drought events in arid and semi-arid rangelands in Alborz province during the growing season was assessed. The results showed that most remote sensing indices in the study area had significant correlations with SPI drought index in long-term scales. It was concluded that LST index was the best index for rangeland areas. This result is compatible with the findings of studies by Mishra et al., (2017), Xu et al., (2018) and Park et al. (2017). Vegetation and thermal indices had high correlations with SPI. This finding is similar to the results obtained by Heydari et al. (2018) and Bento et al. (2018). The results of the ability assessment of single drought indices in monitoring drought indicated that these indices could determine the driest and wettest years well, especially for rangelands.

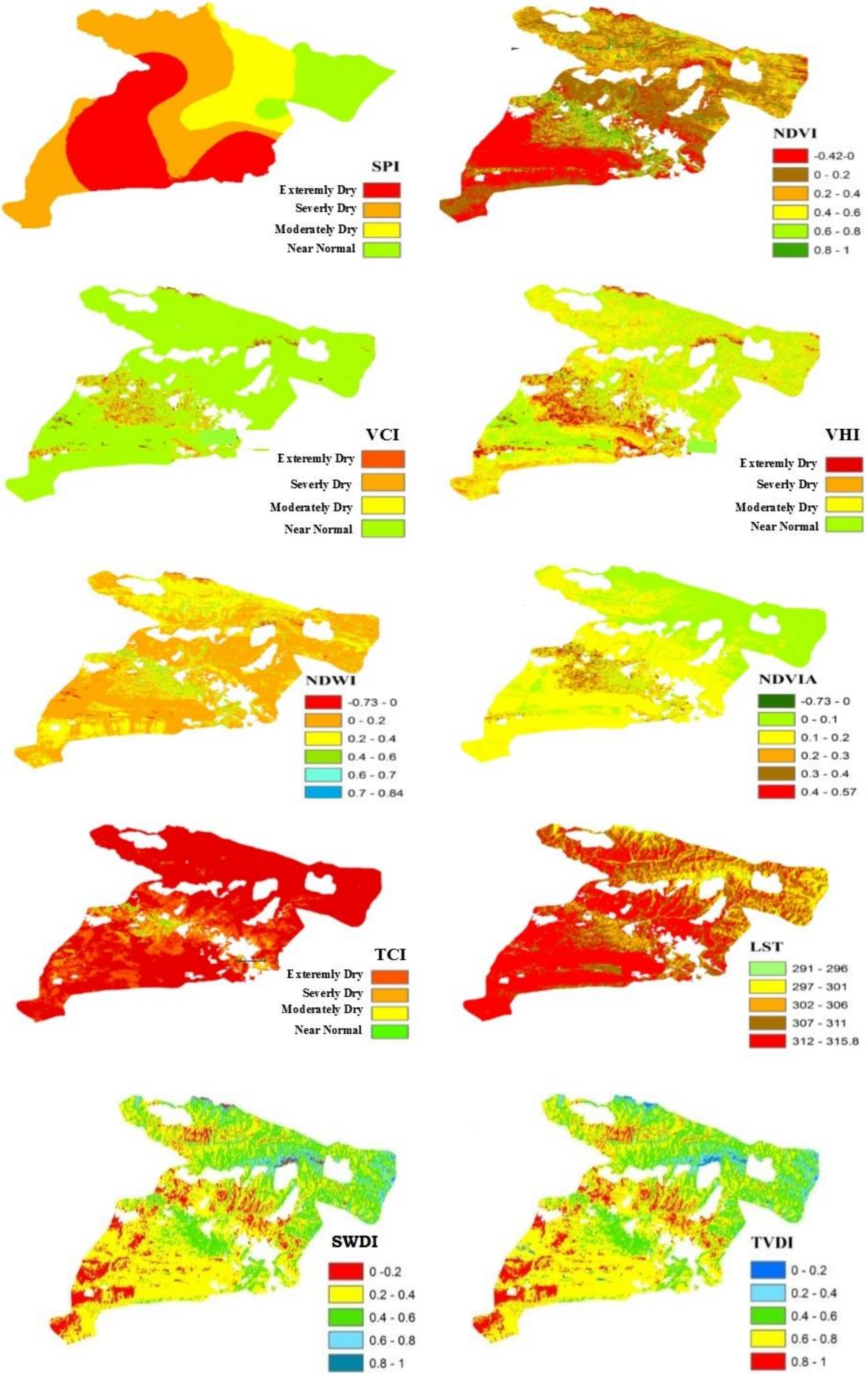

Figure 4. Drought severity by SPI, NDVI, VCI NDWI, NDVIA, TCI, LST SWDI, TVDI, and VHI indices for May in the driest year (2000)

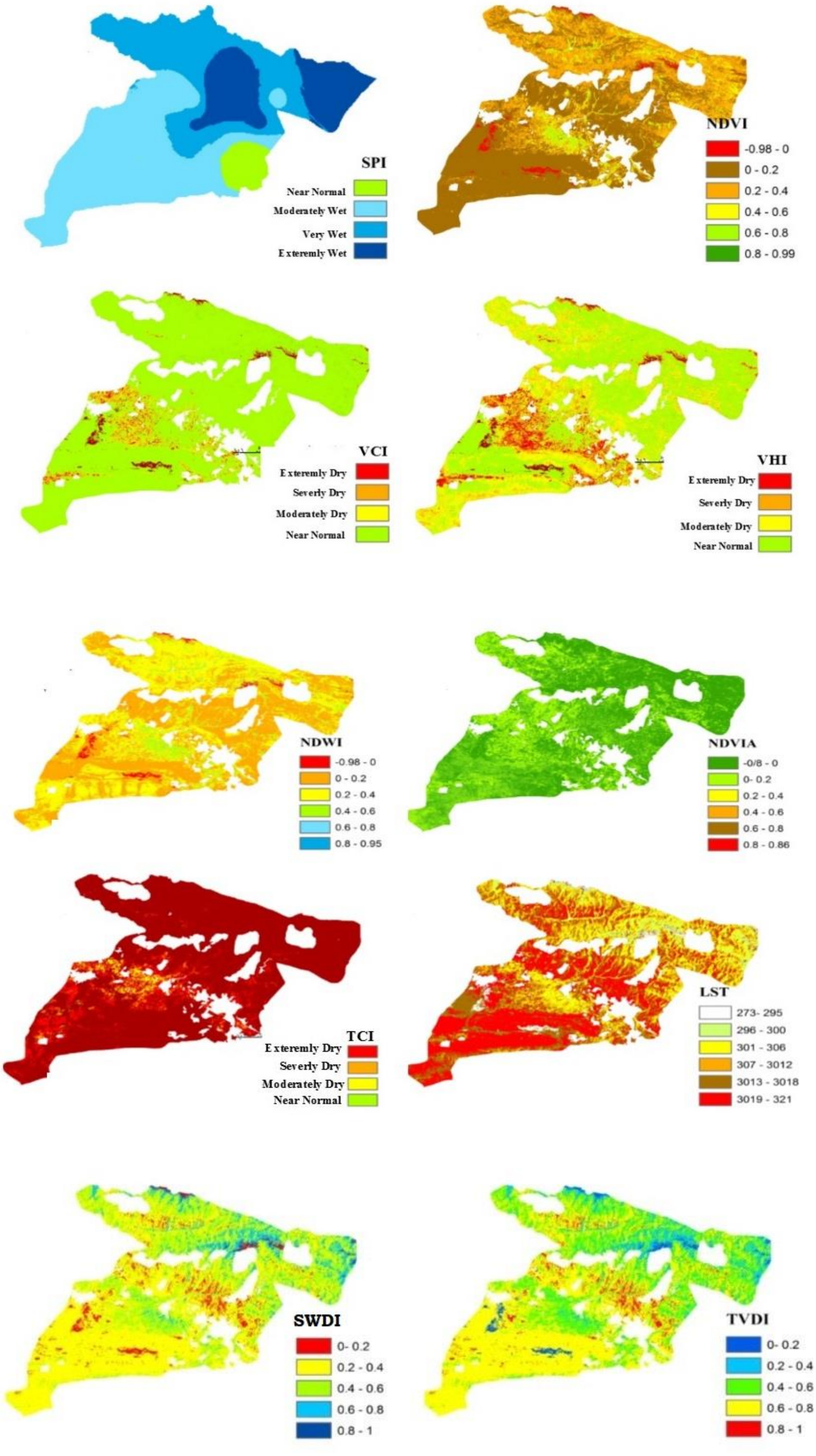
SPI
Near Normal
Moderately Wet
Very Wet
Exteremly Wet
NDVI
-0.98 - 0
0 - 0.2
0.2 - 0.4
0.4 - 0.6
0.6 - 0.8
0.8 - 0.99
VCI
Exteremly Dry
Severly Dry
Moderately Dry
Near Normal
VHI
Exteremly Dry
Severly Dry
Moderately Dry
Near Normal
NDWI
-0.98 - 0
0 - 0.2
0.2 - 0.4
0.4 - 0.6
0.6 - 0.8
0.8 - 0.95
NDVIA
-0/8 - 0
0- 0.2
0.2 - 0.4
0.4 - 0.6
0.6 - 0.8
0.8 - 0.86
TCI
Exteremly Dry
Severly Dry
Moderately Dry
Near Normal
LST
273- 295
296 - 300
301 - 306
307 - 3012
3013 - 3018
3019 - 321
SWDI
0- 0.2
0.2 - 0.4
0.4 - 0.6
0.6 - 0.8
0.8 - 1
TVDI
0- 0.2
0.2 - 0.4
0.4 - 0.6
0.6 - 0.8
0.8 - 1

Figure 5. Drought severity by SPI, NDVI, VCI NDWI, NDVIA, TCI, LST SWDI, TVDI, and VHI indices for June in the wettest year (2005)

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