RESEARCH ARTICLE

Impact assessment of drought monitoring events and vegetation dynamics based on multi-satellite remote sensing data over Pakistan

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Abstract

Drought is a complex hazard caused by the disruption of rainwater balance, and it always has an impact on ecological, farming and socio-economic. In order to protect farming land in Pakistan, effective and timely drought monitoring is extremely essential. Therefore, a regular drought monitoring is required to study drought severity, its duration and spread, to ensure effective planning and to help reduce their possible adverse impacts. In this study, multi-satellite data were used for reliable drought monitoring. For monitoring changing trend of drought in Pakistan, the NVSWI, DSI, VCI, and NAP indices were chosen as a tool incorporated with Moderate Resolution Imaging Spectroradiometer (MODIS)-based NDVI and ET/PET. Due to the low vegetation and significantly high changing trend of drought, NDVI, DSI and TVDI are useful to characterize drought frequency in Pakistan. The yearly DSI index shows that Pakistan suffered of drought with low vegetation during 2001, 2002 and 2006 study years. The seasonal DSI, VCI, NAP, NDVI, and NVSWI values confirmed that 2001, 2002 and 2006 led to severe drought years in Pakistan. The regression analysis between VHI, VCI, NDVI and NVSWI values are significantly positively correlated. The NAP, DSI, and NVSWI showed the positive signs for good drought monitoring indices for agricultural regions of Pakistan. The trend of drought change from 2001 to 2017 also showed characteristics. The results showed that from 2001 to 2017, the drought trend of the whole region changed obviously, and the overall drought frequency showed a downward trend. The good performance of DSI, and NVSWI could, explicitly, contribute progressively towards improving specific drought mitigation strategies and disaster risk reduction at regional and national levels.

Keywords Vegetative changing trends · Drought severity index · NVSWI · Principal component analysis · Pakistan

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Introduction

Continuous periods of abnormally dry climates are considered drought, which may cause hydrological and environmental imbalance with severe impacts on social, economic, and ecological (Wu et al. 2015). Impact depends on drought severity, duration and frequency (Qin et al. 2014). To ensure the impact of global change on drought, it is necessary to monitor drought events correctly and timely (Aljerf 2017). However, drought is defined as a period of insufficient precipitation that affects farming land and natural ecological units (Gao et al. 2017; Lin et al. 2019). Drought is a phenomenon that affects all people, regardless of which area of life they belong to (Adnan et al. 2018a, b). Numerous studies have demonstrated that hazards such as food and drought affect socially vulnerable groups more severely than other hazards (Dhorde and Patel, 2016). Although the Pakistani agricultural regions have adequately guaranteed food

security, it is susceptible to climate change (Khan and Khan 2015). Latif et al. (2018) noted that the seasonal amount of rainfall is influenced by global warming and climate changing. In the coming years global warming and climate change is expected to cause more severe droughts (Safdar et al. 2014), which may lead to land degradation in dry-land farming regions (Hanif et al. 2013). However, a significant improvement in drought intensity and frequency of current era has been observed in South Asia (Zhang et al. 2016).

IPCC (2014) currently reported that between 1880 and 2012, the mean worldwide and ocean surface temperature improved significantly by 0.85 °C. According to IPCC (2014) Pakistan is one of the most drought affected regions in the South Asia, and the IPCC had identified risks of food and rainwater deficiency. For monitoring drought events, a multi-satellite remote sensing data have been a powerful and consistent tool (Yao et al. 2011; Chen and Zhao 2016). Describing the temporal and spatial evolution of droughts is mostly important (Ward and Makhija 2018; Ali et al. 2019); while in contrast, NDVI is used to characterize vegetation status (Zargar et al. 2011; Zhang et al. 2015). Drought is an obvious persistent natural disaster, particularly in the rain-fed farming regions of Pakistan (Leng et al. 2015). Drought causes more agricultural losses than any other natural disaster (White et al. 2003; Ain et al. 2019).

In recent years, TVDI (Rajpoot and Kumar 2019), NVSWI (Jain et al. 2015) and DSI (Guo et al. 2019) which based on NDVI, LST, and ET/PET also attracted the interest of scientists because all of the above drought indices have surface temperature stress (Haque and Basak 2017). Zhang et al. (2021) and Ali et al. (2019) developed universal index such as DSI, which based on MODIS data of NDVI, and ET/PET. Abuzar et al. (2019) reported that MODIS-based ET products have achieved extremely a good indicator for drought monitoring, while NDVI has the potential to link vegetation responses to climate change (Rogelj et al. 2016). Drought conditions persist, especially in the south-west of the country (Huang et al. 2016; Adnan et al. 2018a, b). Widely used vegetation indices include such as VCI and NDVI (Tucker et al. 1986). Multi-satellite remote sensing data have been indicated to be an effective and consistent tool for characterizing the spatiotemporal drought monitoring events (Wang et al. 2014; Chen et al. 2015).

Global warming phenomena further lead to changes in rainfall events. It has been observed that for every 1 °C increase in temperature, the water-carrying capacity of air decreases by 7% (Enenkel et al. 2016). However, multi-satellite-based remote sensing data are readily available and help to identify the occurrence, spatial and temporal magnitude of droughts and have been widely used in the past few years (Abbas et al. 2014; Tadesse et al. 2014). Drought indices can give a degree of drought over a specific period which helps to identify short and long-term drought events and observe

time scales of drought changing trends (Ali et al. 2019). However, a number of vegetation indices have been used for drought evaluation in Pakistan (Ainuddin et al. 2013; Dhorde and Patel 2016; Adnan et al. 2018a, b). But, research gaps remain on the seasonal effects of rainfall and temperature in a selected region.

Pakistan is more concerned about climate change. With projected warming likely to increase drought frequency, effective drought monitoring methods are critical and can be used for mitigation and policy implementation in a timely manner. The purpose of this study is to fill the literature gap by examining three main objectives: (1) by using MODIS derived drought indices such as DSI, NVSWI, TVDI and NAP to identifying the best drought monitor index in Pakistan; (2) by determining the optimal drought indices in different climatic zones of Pakistan and determine the time lag between precipitation and drought; and (3) to explore spatiotemporal patterns and trends in vegetation and drought in Pakistan over the past 17 years.

Study area and data analysis

Study area

Pakistan is located in South Asia, between east longitude (61°-78°) and north latitude (23°-38°). The annual mean rainfall was calculated by the Tropical Rainfall Measurement Mission (TRMM) for the period of 2001–2017. The average rainfall in Pakistan is 307 mm (1991–2020). Rainfall varies by region. The southern and western regions receive less than 150 mm per year, while the northern and eastern regions can receive 400 to 1000 mm. The national average temperature was 21 °C (1991–2020). The land use and land cover map of Pakistan was obtained by using the MODIS (MCD12Q1) product which clearly highlights all the land surface features (Fig. 1).

Data processing and analysis

Drought Severity Index (DSI)

DSI was proposed by Mu et al. (2013) for this purpose, MODIS NDVI monthly product (MOD13A1) and product (MOD16A2) for ET/PET at 1 km resolution was used to derive DSI value.

$$Ratio = \frac{ET}{PET} \tag{1}$$

The temporal mean (Ratio) and standard deviation (σRatio) of Ratio were determined by given equation.
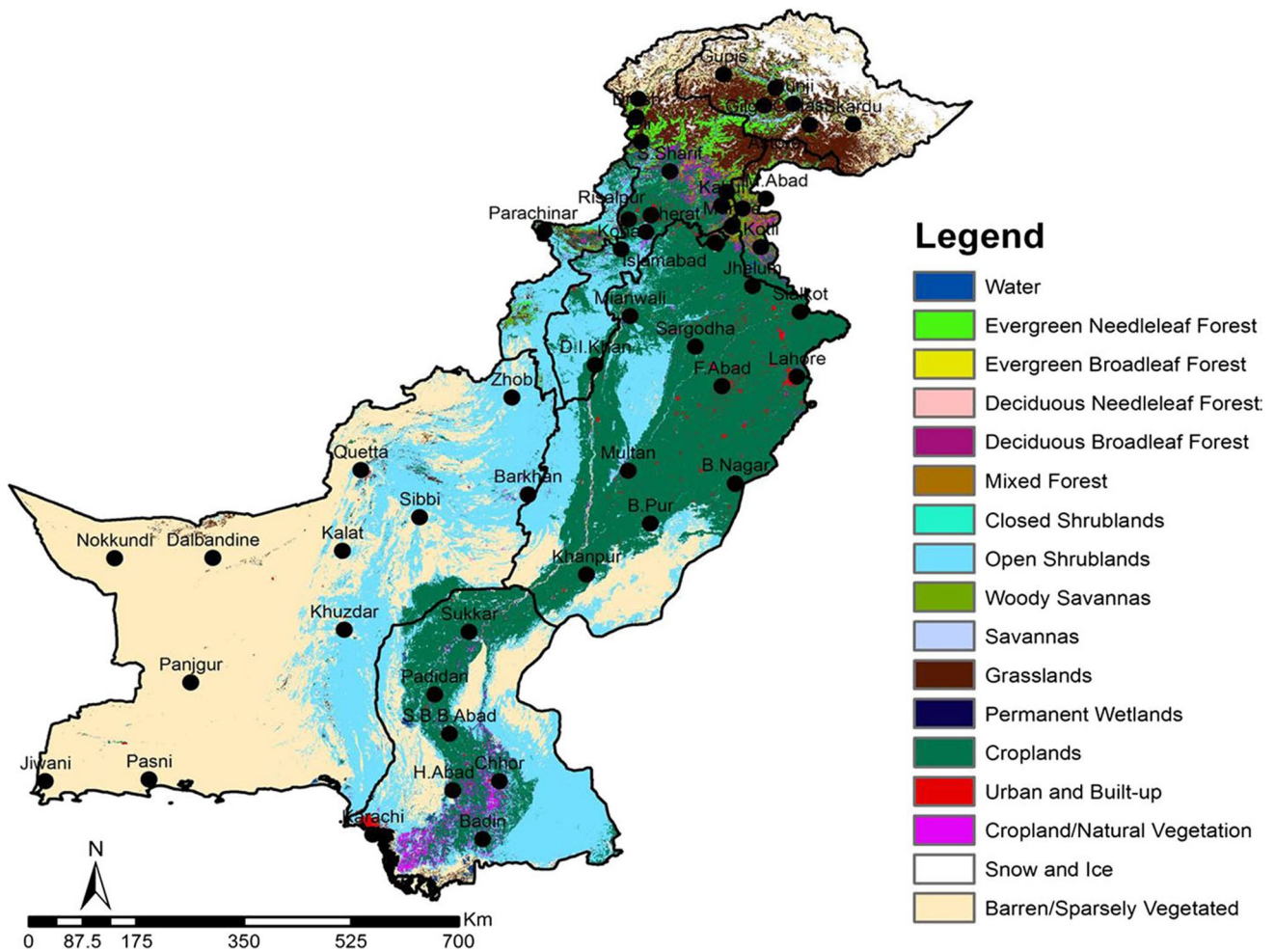
Fig. 1 Land cover map of Pakistan

$$Z_{Ration} = \frac{Ratio - \overline{Ratio}}{\sigma_{Ratio}} \quad (2)$$

Similarly, NDVI values at each grid cell were normalized by mean NDVI and standard deviation (σ_{NDVI}) to get Z_{NDVI}.

$$Z_{NDVI} = \frac{NDVI - \overline{NDVI}}{\sigma_{NDVI}} \quad (3)$$

Both Z_{Ratio} and Z_{NDVI} values were carried out to get Z value.

$$Z = Z_{Ratio} + Z_{NDVI} \quad (4)$$

The DSI value was finally calculated as

$$DSI = \frac{Z - \overline{Z}}{\sigma_Z} \quad (5)$$

The DSI categorizes the drought severity.

TRMM3B43

Monthly TRMM3B43 product extends from 50°N to 50°S with a spatial resolution of 0.25°, while monthly rainfall from January to December 2001–2017 from NASA's (http://reverb.echo.nasa.gov/) was used to determine monthly mean precipitation for Pakistan. The TRMM3B43 product was used to calculate the NPA value.

Monthly Precipitation Anomaly Percentage (NPA)

The PA is the precipitation deficit compared to the average for the same period. The PA was determined by given equation (Shao and Bing-Fang 2010).

$$PA = \frac{P - \overline{P}}{\overline{P}} * 100\% \quad (6)$$

where P is the present precipitation and Ṕ is the mean precipitation. The value of PA can be positive or negative. The NPA value from 0 to 1 and can be determined by given Eq. (7).

$$NPS = \frac{PA - PA_{min}}{PA_{max} - PA_{min}} \tag{7}$$

where PA_{max} and PA_{min} are the maximum and minimum values of the PA.

Vegetation Condition Index (VCI)

The VCI recommends normalizing NDVI relative to the minimum and maximum NDVI values. The formula for calculating VCI is as follows (Kogan 1998).

$$VCI = \frac{NDVI - NDVI_{min}}{NDVI_{max} - NDVI_{min}} \tag{8}$$

Normalized Vegetation Supply Water Index (NVSWI)

When vegetation suffers from drought, insufficient soil moisture causes leaf stomata to partially close to maintain moisture in the canopy, as a result ET decrease and increase LST (Abbas et al. 2014).

$$VSWI = \frac{NDVI}{LST} \tag{9}$$

The NVSWI is calculated by the given formula (Ali et al. 2019).

$$NVSWI = \frac{VSWI - VSWI_{min}}{VSWI_{max} - VSWI_{min}} \tag{10}$$

where $VSWI_{max}$ and $VSWI_{min}$ are maximum and minimum values of VSWI of each pixel. The NVSWI values are divided into five intensity categories (Table 1). Figure 2 shows the research flowchart.

Drought tendency rate

To analyze whether drought in Pakistan increased or decreased from 2001 to 2017, drought trend rates were based on NVSWI values.

$$Slope = \frac{n * \sum_{i=1}^{n}(1 * F_i) - \left(\sum_{i=1}^{n} i\right) * \left(\sum_{i=1}^{n} F_i\right)}{n * \sum_{i=1}^{n} i^2 - \left(\sum_{i=1}^{n} i\right)^2} \tag{11}$$

Table 1 Drought categories for NVSWI

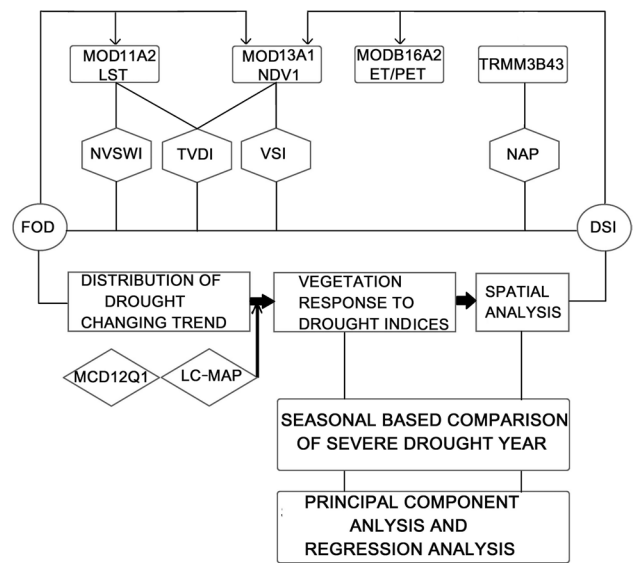|	Severe	Moderate	Slight	Normal	Wet
NVSWI	< 0.20	0.20–0.40	0.40–0.60	0.60–0.80	> 0.80

Fig. 2 Flowchart of comprehensive drought monitoring based on multi-source remote sensing data. Note: FOD: Frequency of drought; DSI: Drought severity index

where i is the year, n is the time series length, and F_i is the frequency of drought in each year. A positive slope means that the drought frequency is rising and the degree of drought is getting worse. Conversely, a negative slope indicates an increasing trend in degree of drought.

Spatial Correlation

All the variables were used for correlation analysis (rxy).

$$r_{xy} = \frac{\sum_i (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_i (x_i - \bar{x})^2 \sum i (y_i - \bar{y})^2}} \tag{12}$$

where y response NDVI and x is the predictor climate variables.

Results and Discussion

Monitoring of drought changing trend by using DSI

The NDVI is a good indication for identifying drought-prone areas. At a larger level, however, NDVI values are difficult to identify as indicators of drought, as vegetation is influenced not only by climatic features but also other numerous restricted factors. Therefore, DSI was calculated by using MODIS-derived ET/PET and NDVI with excellent resolution was used as a tool to monitor droughts. Yearly DSI values for Pakistan over the past 17 years were used to classify dry regions and severe drought years (Fig. 3).

Fig. 3 Annual drought severity index (DSI) anomaly values over Pakistan for the period of 2001 to 2017
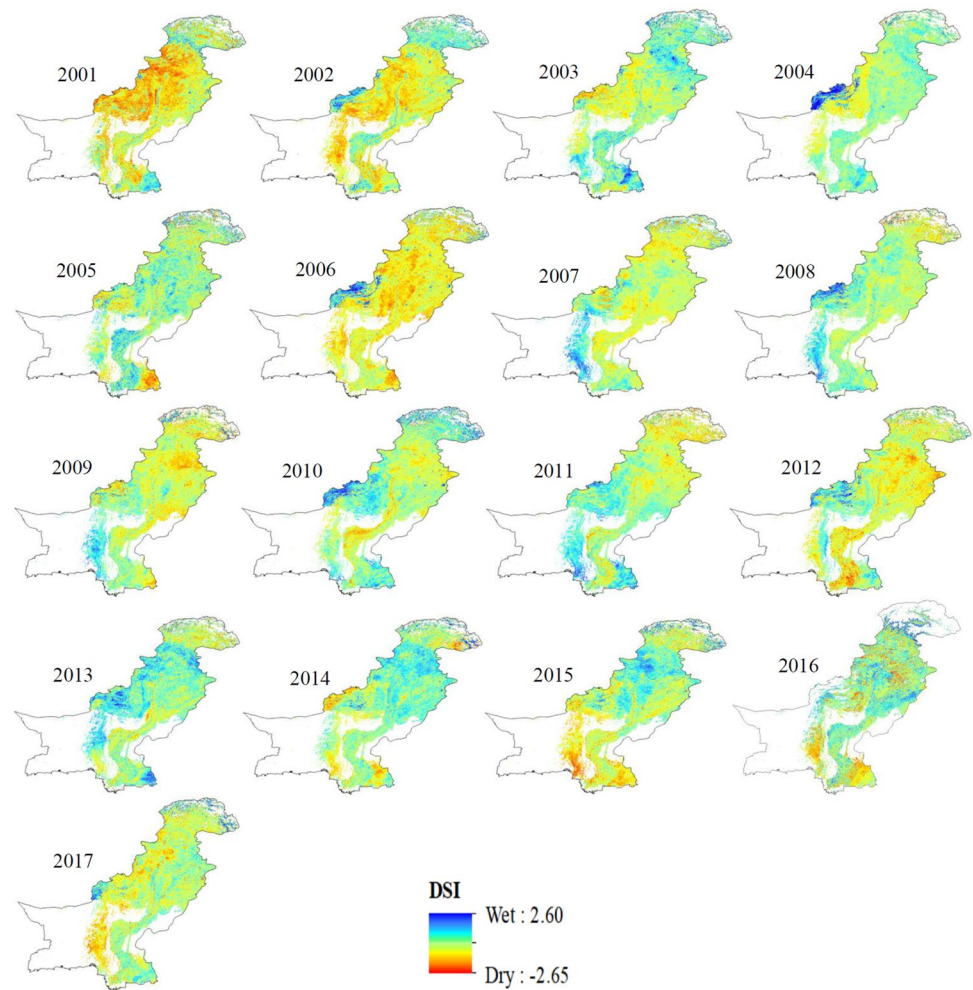

Areas affected by drought are classified annually using spatial maps. On a seasonal base, mean DSI was classified into three severe drought years, such as 2001, 2002, and 2006 (Fig. 4). The persistent drought in 2001–2002 may have been caused by ENSO events in the tropical Pacific that resulted in a weakening of the summer monsoon, resulting in drier conditions in Pakistan (Dai 2011). One study showed that seasonal variation in DSI values is significant for short-term dry periods. On a regional base, these maps are simple to recognize drought severity due to the designed dimensionless index. According to Mu et al. (2013) the DSI category defined as, DSI values greater than or equal to 1.5 are measured extremely wet conditions, and values less than or equal to -1.5 consider extremely dry conditions. The spatial map shows that extreme drought environment in 2001 began to extend during the spring (MAM) season in the K.P province. The occurrence and length of a drought monitor by DSI are dependable with the outcome of meteorological drought published in other journals (Duan et al. 2012). But, the normal onset of the late monsoon provides sufficient rainwater for vegetation, so the water shortage in the summer (JJA)

season is no longer evident excluding in the higher areas of K.P province. Severe drought in Sindh started to extend during the 2002 summer (JJA) season and continued into the 2006 spring (MAM) season. In 2006, the northern region was again affected by the extremely dry weather during the Autumn (SON) season. Anomalous negative DSI is linked with aridity; positive value is associated with humidity. The seasonal DSI has recognized severe drought regions that occurred in 2001, 2002 and 2006 years. USDA (2011) also reported officials called the worst drought period in past 50 years. The results showed that the DSI in 2001 was recorded worst, with a very low yearly DSI of -2.65 over Pakistan.

Seasonal evaluation of NVSWI and NPA in Pakistan

In order to choose the most appropriate drought indicators for Pakistani region, the performance of NVSWI and NPA was evaluated. For a specific degree of drought description, the two drought indexes such as NVSWI are divided into five grades: extreme, moderate, mild drought normal and humidity

Fig. 4 Seasonal average DSI distribution for the historic drought event, DJF: Dec-Feb, MAM: Mar-May, JJA: Jun-Aug and SON: Sep-Nov, over Pakistan during (2001, 2002, 2006)
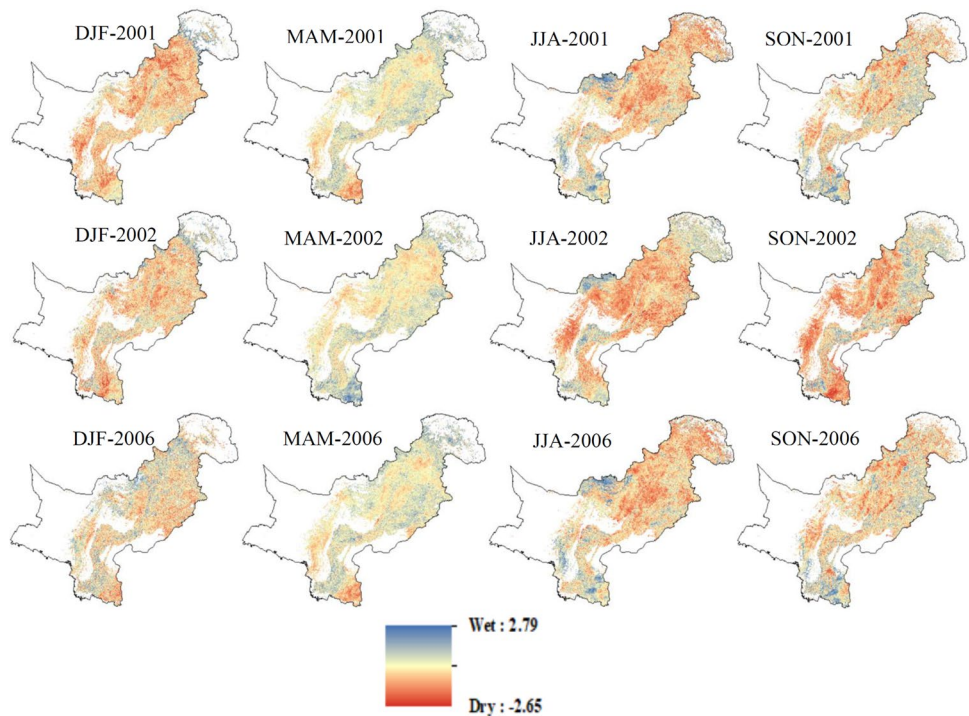
conditions. Additionally, the seasonal averages of NVSWI and NPA of three extreme severe drought years (2001, 2002 and 2006) are successively chosen to confirm the drought monitoring ability. The spatial distribution patterns NVSWI and NPA

drought indices of Pakistan are shown in Figs. 5 and 6, respectively. Regression analysis among the drought indexes demonstrated the significant of NVSWI index. However, the NAP has been used in previous studies to verify the performance of

Fig. 5 Spatial distribution of seasonal average NVSWI values, DJF: Dec-Feb, MAM: Mar-May, JJA: Jun-Aug and SON: Sep-Nov, over Pakistan during (2001, 2002, 2006)
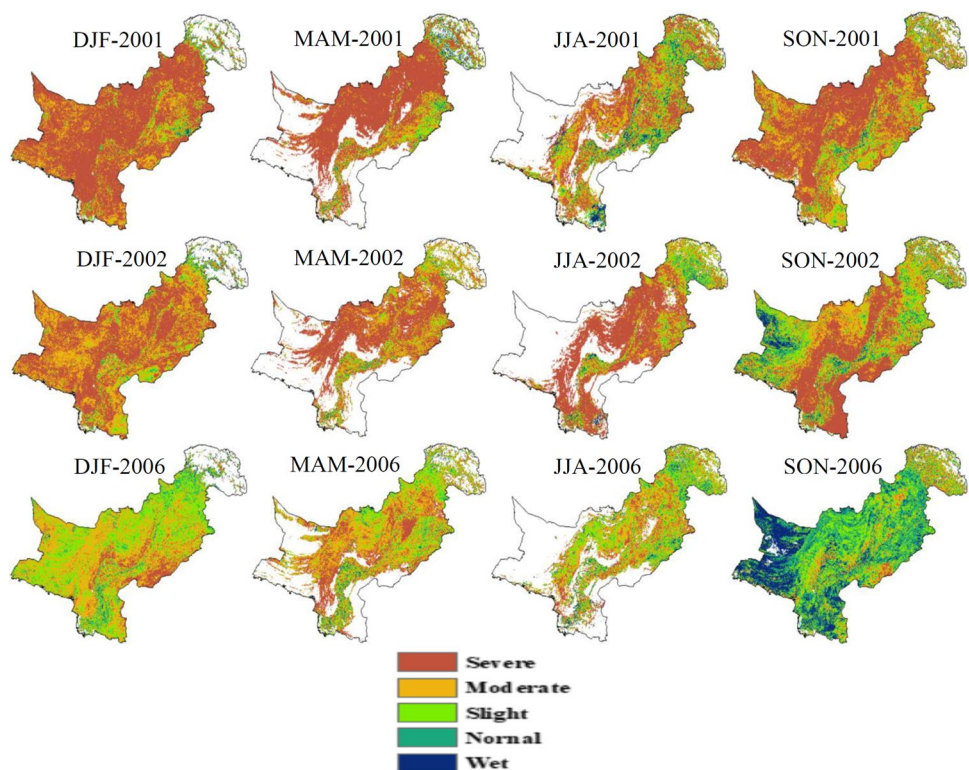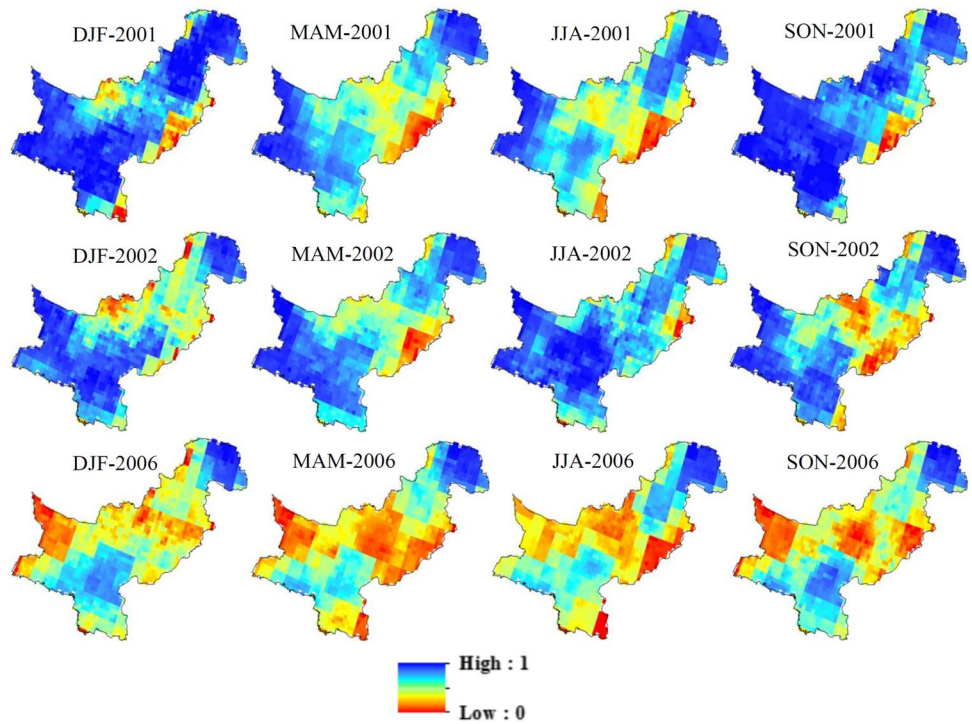
Fig. 6 Spatial distribution of seasonal average NAP values, DJF: Dec-Feb, MAM: Mar-May, JJA: Jun-Aug and SON: Sep-Nov, over Pakistan during (2001, 2002, 2006)

drought mentoring (Jain et al. 2009; Abbas et al. 2014). The effectiveness of TRMM has been established in other regions by many research works (Abbas et al. 2014; Song et al. 2014). In various growing seasons, the NVSWI indices identify the Northeast and its surrounding areas as wet areas. However, western and eastern Pakistan had the largest NPA values from spring to summer season, as a result of high vegetation coverage due to high rainfall and NDVI values. NVSWI values verify that drought in southwestern Pakistan has increased in various seasons, while NPA shows the opposite due to low rainfall and high LST. Due to the irregular rainfall distribution, the NPA distribution pattern is not uniform. Therefore, considering the NVSWI performs better among the three drought indices for drought mentoring in Pakistan (Fig. 5).

Fig. 7 Spatial distribution of seasonal average VCI values, DJF: Dec-Feb, MAM: Mar-May, JJA: Jun-Aug and SON: Sep-Nov, over Pakistan during (2001, 2002, 2006)
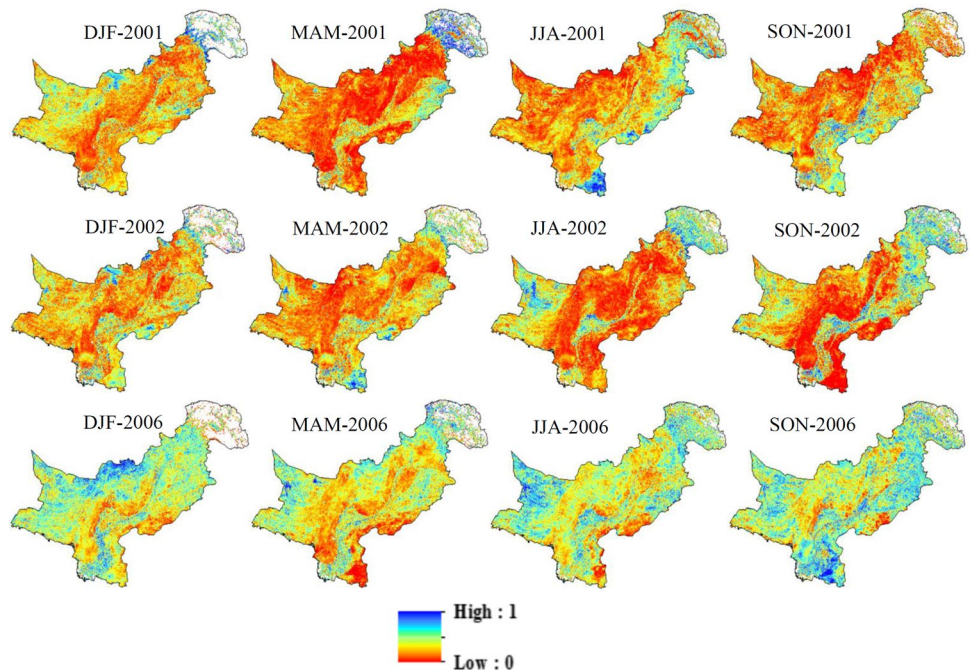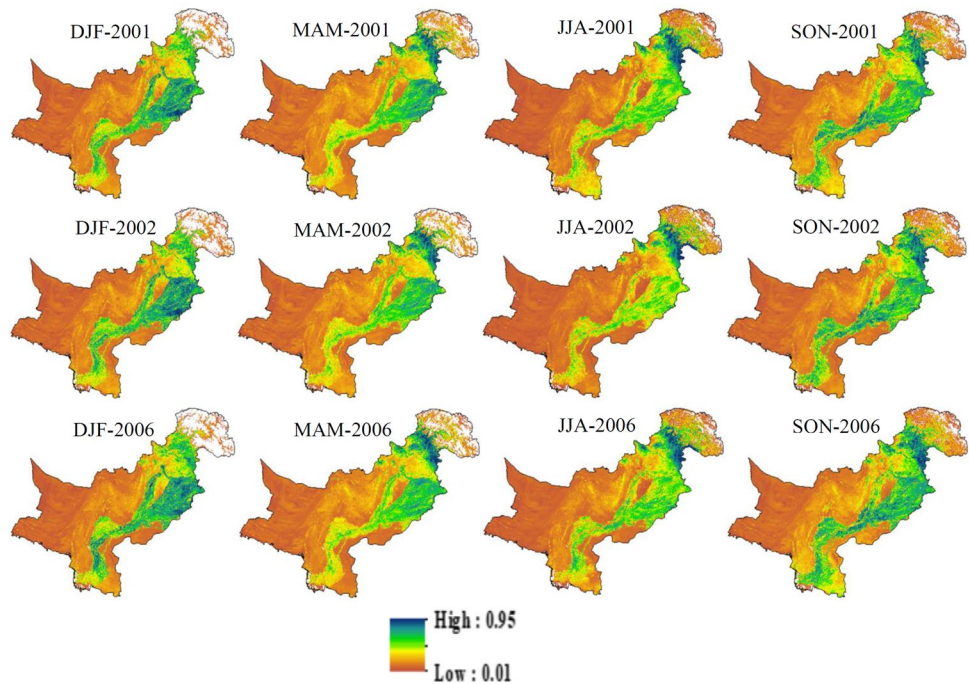
Fig. 8 Spatial distribution of seasonal average NDVI values, DJF: Dec-Feb, MAM: Mar-May, JJA: Jun-Aug and SON: Sep-Nov, over Pakistan during (2001, 2002, 2006)


The NVSWI standardized based on VSWI values (Jackson et al. 2010). Distribution maps from NVSWI indicated that during spring and autumn most part of Pakistan has severe drought. But, monsoon precipitation starts in summer and provides sufficient soil moisture for vegetation growth, while rainwater deficiencies do not occur in autumn except in west and east region of Pakistan. Measuring drought conditions in different parts of Pakistan, the NVSWI were considering the most suitable for drought monitoring. Several earlier research works also confirm that NVSWI is a good drought monitor index (Crow et al. 2010; Abbas et al. 2014). In general, after rainfall the NPA only monitors drought conditions. A little

precipitation in the western part of Pakistan so NAP did not measure the drought changing trends (Zhang et al. 2016).

Seasonal evaluation of NDVI and VCI distribution values

Rouse et al. (1973) originally used NDVI for vegetation assessment. The NDVI itself does not reveal an arid or non-arid environment; however, it indicates the drought severity by measure the difference between the present NDVI and normal NDVI circumstances (Jain et al. 2009). In this research, monthly MODIS NDVI was used to calculate

Fig. 9 Distribution of the drought change trend in Pakistan for the period of 2001 to 2017
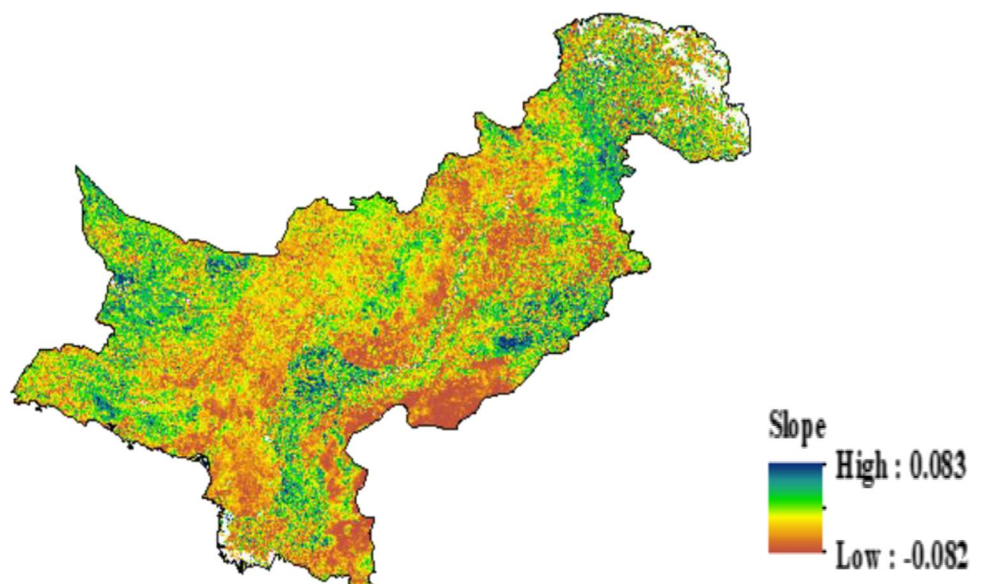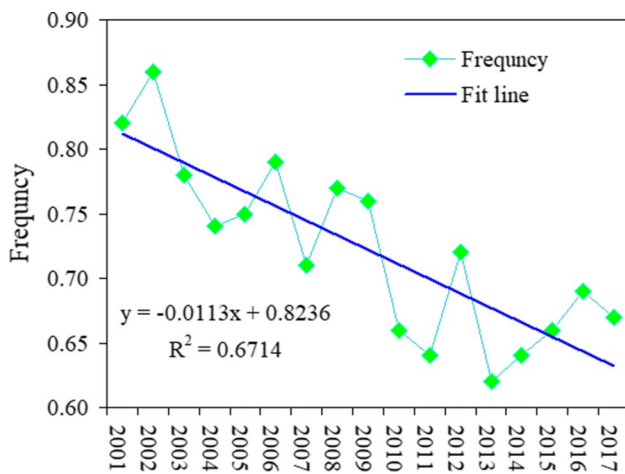
Fig. 10 Frequency of drought occurrence in Pakistan for the period of 2001 to 2017

seasonally averaged NDVI values. NDVI and VCI values were zero, indicating very low vegetation, which is associated with arid climates (Fig. 7 & 8). These seasonally averaged VCI and NDVI maps have been recognized and assessed to categorize the drought effect regions of Pakistani. Over the period of 2001–2017 seasonally averaged NDVI and VCI maps showing general vegetation dynamics. The spatial distribution pattern of VCI, NDVI, rainfall, and air temperature has the same variation, which is a good sign for dividing drought prone regions. The mean VCI and NDVI were produced seasonally during the study period, show severe drought in Pakistan (Fig. 7 & 8). Vegetation in Pakistan is also on the rise. However, Pakistan is less consistent due to rapid urbanization (Wang et al. 2001). In the northwestern part of Baluchistan is relatively poor economic development and human activities having significantly an impact on the vegetation. But, in current years the influence of natural and anthropogenic aspects on vegetation may have contributed to the low vegetation (Hou et al. 2018). Zhao et al. (2018) and Luo et al. (2014) reported that VCI and NDVI correspond to climatic aspects such as temperature and rainfall and can be used as drought monitoring indices. The spatial map confirms that during winter season (DJF) in a different province of Pakistan is very dry. But, the summer monsoon (JJA) can supply sufficient moisture for vegetation growth. As a result, the water stress in autumn (SON) is not obvious except in the northwestern part of Pakistan. Maximum values of NDVI and VCI are recorded in the summer season (JJA) in a different province of Pakistan. The VCI and NDVI distribution values showed an upward movement from spring to summer seasons, while VCI and NDVI during autumn (SON) were again higher than those in winter (DJF) seasons. Ashraf (2016) report that Pakistan suffers severe drought in winter and Qaiser et al. (2021) also report that

the drought is more severe in northwestern Pakistan than in southeastern Pakistan. Relatively low temperatures in spring may also negatively affect vegetation dynamics and drought trends and frequencies (Liu et al. 2015).

Drought change trend and frequency distribution in Pakistan during last 17 years

In order to explain the distribution of drought change trend in detail since 2001 to 2017, and drought frequency from 2001 to 2017 was summarized, including severe, moderate, and mild droughts. Then, the annual drought incidence and the drought trend in the past 17 years were calculated. Figure 9 shows the distribution of drought slopes in Pakistan. Compared to the past 17 years, the degree of drought in western and eastern Pakistan has decreased. However, over the past 17 years, the central, northern and southern parts of Pakistan have been more frequently affected by drought. Figure 10 shows the frequency of droughts in Pakistan over the past 17 years, with no apparent regularity. The year with the highest drought frequency was 2002 (0.87), which was consistent with the year with the least rainfall and the most severe drought in 2002 (Fig. 6). The least frequent drought occurred in 2013 (0.61), which may be due to higher rainfall (Fig. 3). The slope of the fitted line is negative with -0.0113 values, which signifying an in general decrease trend in frequency of drought from 2001 to 2017.
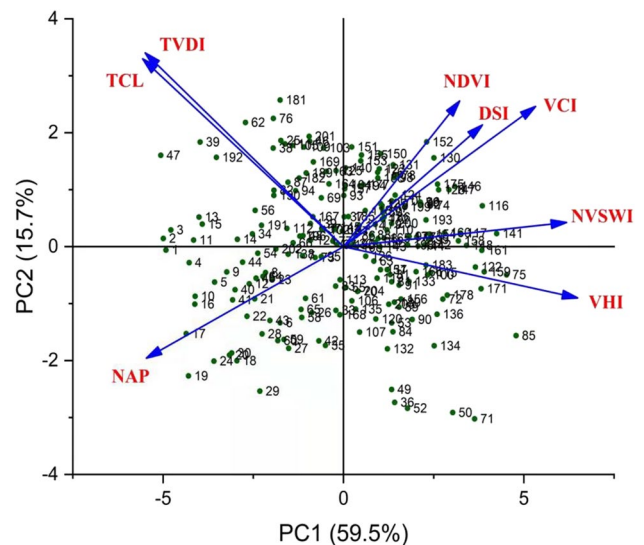

Fig. 11 Principal component analysis of the drought indexes obtained by the Vegetation Health Index (VHI), Normalized Difference Vegetation Index (NDVI), Normalized Monthly Precipitation Anomaly Percentage (NAP), Temperature Vegetation Drought Index (TVDI), Vegetation Condition Index (VCI), Temperature Condition Index (VCI), Drought severity index (DSI), and Normalized Vegetation Supply Water Index (NVSWI)
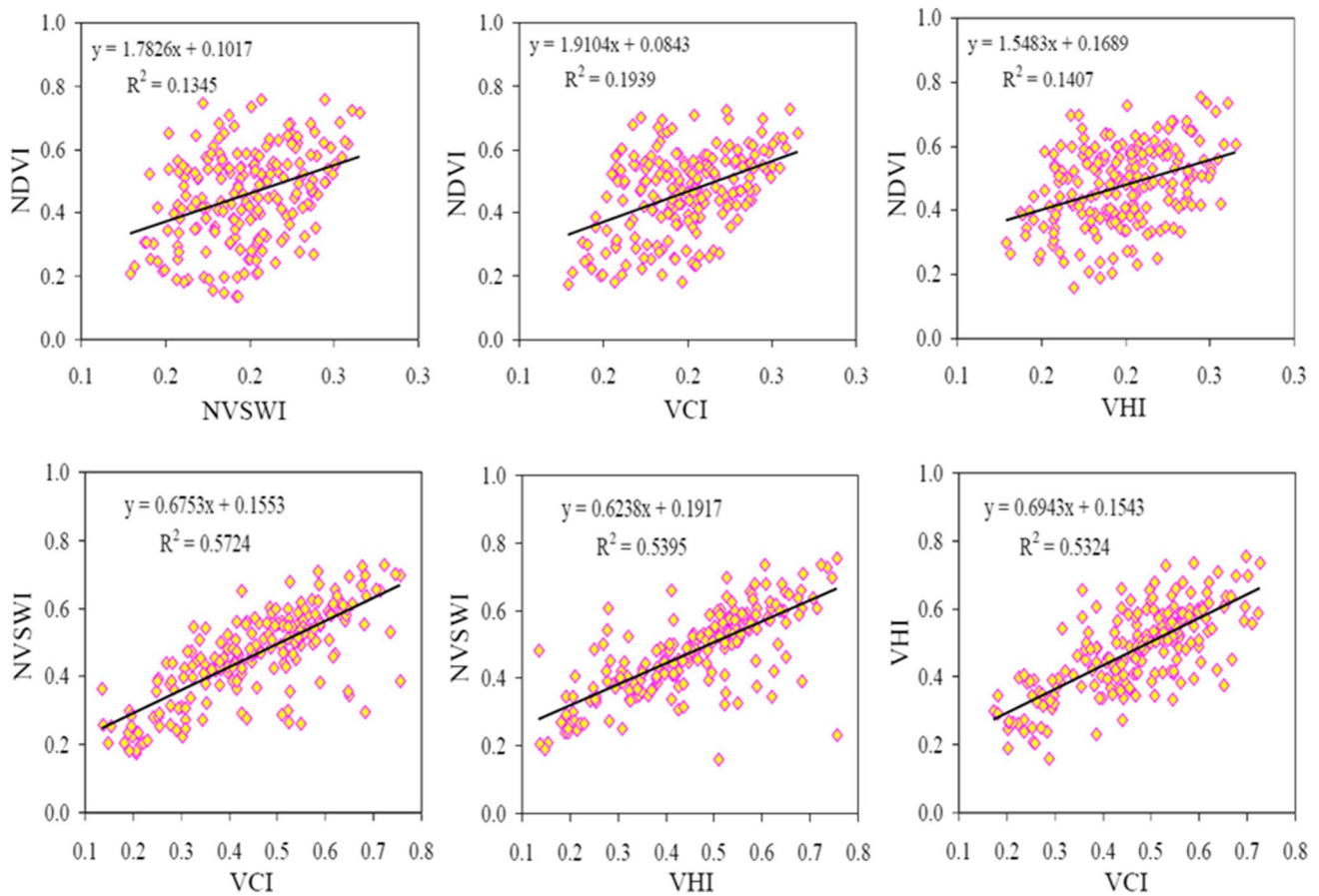
Fig. 12 Regression relationships of the drought indexes obtained by the Vegetation Health Index (VHI), Normalized Difference Vegetation Index (NDVI), Normalized Vegetation Supply Water Index (NVSWI), Vegetation Condition Index (VCI), Vegetation Condition Index (VCI)

Principal component analysis and spatial correlation analysis

The total variance of the data represents in the four principal counts component. The first (PC1) component represents a vector in n-dimensional space that is linked to the largest parameter change. In the data set analysis that the 1st (PC1) component represents a vector that accounts for 59.5% of the total variance, while the 2nd (PC2) component represents a vector in the plane perpendicular to PC1. The PC2 revealed the largest change of 15.7% of the total variance (Fig. 11). Figure 12 confirms an important combination of NAP, TCI, NDVI, VCI, DSI, TVDI, NVSWI, and VHI indices. DSI was non-considerably associated with TCI, TVDI and NAP values, but was considerably associated with NVSWI, VCI, NDVI and VHI values. The spatial correlation analyses of the drought indices are revealed in Fig. 12. There were considerable a positive regression link between NVSWI and NDVI, VCI and VHI drought index, VCI and VHI with NVSWI values. Furthermore, a significant positive correlation was observed between the VCI and VHI drought indices. From these vegetation and drought monitoring indicators, it is confirmed that this is a comprehensive sign of climate change in Pakistan and monitor drought and vegetation trends.

Conclusion

The northwestern region of Pakistan faces moderate drought for most of the year, but conditions have been exacerbated by the failure of monsoon rains. The study confirmed that Pakistan has been experiencing loss of vegetation cover due to drought and that the DSI, NDVI, and TVDI drought indices are more helpful in describing drought events trends. Due to the low vegetation and significantly high changing trend of drought, NDVI, and DSI are useful to characterize drought frequency in Pakistan. The yearly DSI index shows that Pakistan suffered of drought with low vegetation during 2001, 2002 and 2006 study year. Seasonal DSI, VCI, NAP, NDVI, and NVSWI values confirmed that Pakistan suffered from severe drought during 2001, 2002 and 2006 leading to severe drought years. The spatial correlations between VHI, VCI, NDVI and NVSWI values were

significantly positively correlated. DSI, NVSWI and NAP show positive signs of good drought monitoring indices in Pakistan's agricultural areas. Northwest China suffers from disasters in winter, spring, summer and autumn. The temporal pattern of drought is obviously affected by seasonal changes, and the frequency of summer drought in North-east region of Pakistan is higher. From 2001 to 2017 the drought changing trend also characteristics. The results showed that the drought changing trends varied significantly in various regions of Pakistan, and overall the frequency of drought showed a declining trend during 2001 to 2017. The findings of this study can help a strategic decisions maker to prevent future environmental, drought, and vegetation degradation.

Authors' contributions The manuscript was reviewed and approved for publication by all authors. SA, AB, and JN conceived and designed the research. SA and AB performed the research work. SA and AB analyzed the data. SA and AB wrote the paper. FUK, MS, TAM reviewed and revised the paper. JN FUK, MS, and TAM corrected the English language for the paper.

Data availability The availability of data and materials on the base of personal request.

Declarations

Ethical approval The manuscript was reviewed and ethical approved for publication by all authors.

Consent to participate The manuscript was reviewed and consents to participate by all authors.

Consent to publish The manuscript was reviewed and consents to publish by all authors.

Conflict of interest The authors declare that they have no conflict of interest.

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