Quantification of Water Resource Sustainability in Response to Drought Risk Assessment for Afghanistan River Basins

Rahmatullah Dost and K. S. Kasiviswanathan

Drought in Afghanistan has many impacts from the interaction between environmental and socio-economic factors in the agriculture and water supply sectors. The complex topography and climate change impacts cause high spatial and temporal variation in the precipitation pattern and pose several challenges in managing water resources. Therefore, this paper aimed to quantify the sustainability of water resources against the progression of drought. Observed monthly precipitation data monitored by 23 stations located across five river basins covering the entire country for the period 1970–2016 were used to demonstrate the potential impacts of drought on water resources sustainability. Based on severe drought estimation, the year 2000 and 2001 were identified as change points. Accordingly, datasets pertaining to before and after the change points were partitioned to analyze the long-term temporal shift of drought. The spatiotemporal variability of sustainability indicators was estimated using reliability resiliency and vulnerability concept. The results indicated a positive trend of precipitation in most of the river basins after the change points leading to an increase in sustainability. However, the major portion in the upstream of the Kabul River basin showed a decrease in sustainability of around 15% due to a reduction in precipitation. As the Kabul city has high population density, it needs immediate attention in effectively planning and managing available water resources. Furthermore, the comprehensive analyses reported in this paper discuss the possible implications of drought risk assessment and its impact on largely varying sustainability both spatially and temporally in Afghanistan.

KEY WORDS: Drought, Kabul River basin, RRV concept, Spatiotemporal variability sustainability.

INTRODUCTION

Droughts are critical and impose major threats to ecosystems, hydrology, agriculture, economic and social life (Hosseini et al., 2021). The complex nature of droughts has affected all regions of the world, leading to several environmental disasters and, in some cases, irrespective of the amount of precipitation (Bazrafshan et al., 2014). In tropical and subtropical regions, droughts are more common and are expected to intensify in duration and severity (Sheffield et al., 2012). It is highly evident that South Asian regions have been frequently affected by severe drought in the past decade (Sharma et al., 2021). Afghanistan, a country situated in the subtropical region, is no exception to this and it has experienced severe droughts in the recent past. More notably, climate change and its interaction with complex topography have been causing significant socio-economic and eco-environmental damages (World Bank Report, 2018).
Further, the effects of drought are expected to get amplified due to the influence of global warming and consequent climate change. Therefore, challenges in process understanding and modeling of drought characteristics both spatially and temporally are crucial. For better understanding of droughts at the regional scale, the spatial extents and temporal variation from the patterns of previous drought events need to be studied. Moreover, prior knowledge of spatial–temporal dynamics of droughts can assist in better monitoring and managing future drought events effectively (Brunner et al., 2021). However, several challenges still exist while characterizing the spatial–temporal process of drought relating to the sustainability of available water resources in the region. Sustainability is, in general, defined as the ability to maintain water resources at a specific rate or level to meet various demands. Effectively managing the sustainability of water resources both spatially and temporally is important for food security and thus to enhance the livelihoods of the population, especially those who are living in rural areas (Ahmed et al., 2019a, b).

For this endeavor, the reliability resiliency and vulnerability (RRV) concept has been shown to produce a reasonably good estimate of sustainability among several techniques such as Markov Chain, crop moisture index (CMI), Palmer drought severity index (PDSI), and surface water supply index (SWSI). The RRV concept was developed mainly for characterizing long-term drought occurrence due to low-frequency variability and change in climate at a decadal time frame (Machiwal et al., 2020). Following that, several studies (Tsai et al., 2009; Rodak et al., 2014; Ahmed et al., 2019a, b; Lu et al., 2019; Mojid et al., 2019; Sediqi et al., 2019; Machiwal et al., 2020; Golmohammadi et al., 2021; Shiru et al., 2021) have explored the RRV concept in a wide variety of water resources problems. These include the assessment of sustainability in groundwater and surface water systems, besides assessing the sustainability of drought in the region. However, to assess temporal variation of sustainability, the existing method has to be modified. In such a situation, drought indices linked with RRV concepts were proposed. However, only a very few studies have attempted using them. For instance, Greeted et al. (2015) studied a pattern of trends in sustainability governance for agricultural value chains. Kundu et al. (2007) analyzed the long-term yield trend and sustainability of the rainfed soybean–wheat system.

The RRV indicators are analyzed based on drought characteristics. For quantifying drought characteristics, drought indices are employed as the basic tools in monitoring and assessing drought progression and thus for effective water resource management and decision-making (Hong et al., 2015). Several drought indices have been developed and the most commonly used indices are CMI, PDSI, and standardized precipitation index (SPI), as well as SWSI. Calculation of these indices generally requires continuous and consistent data such as precipitation, soil moisture, temperature, pressure, humidity, heat, and crops related data at the field level. While many of these data are unavailable in most countries, especially in a developing country such as Afghanistan, the SPI, which needs only precipitation data (McKee et al., 1993), is often used. Moreover, precipitation can be the indicator for diagnosing the impact of climate change (Cannarozzo et al., 2006). In many cases, the probability of drought can be linked directly to decreasing precipitation (Caloiero et al., 2019). This is mainly because variations in precipitation are expected to produce profound effects on changing the streamflow pattern, soil moisture, and groundwater storage. Moreover, the SPI has several advantages over the other indices, such as (a) being widely used in many places and proved to be effective, (b) flexible in calculating drought at different time scales, (c) various types of droughts can be linked, and (d) stable in terms of spatial structure compared to other indices (Bazrafshan et al., 2014). The detailed description and the advantages of using SPI and its calculation are available in a wide range of literature (Wu et al., 2005, 2007; Paltineanu et al., 2009; Karavitiset et al., 2011; Bazrafshan et al., 2014). Moreover, Blain (2011) assessed changes in SPI final values when computed based on Gamma II-parameters and Pearson Type III. Also, Hong et al. (2015) used the entropy theory to derive a joined probability distribution function for various cumulative precipitation series for the calculation of SPI. As SPI determines drought intensity and magnitude using the scale factor ranges between zero and one, moderate and severe droughts can be classified easily (Chen et al., 2009).

While limited studies on spatial variations of sustainability in water resources are conducted using the SPI–RRV concept, no studies have found a multi-drought threshold to analyze the temporal variations of sustainability assessment pertaining to the frequency of severe droughts. Thus, it is required...
to develop a method for understanding the temporal sustainability of water resources. Moreover, this is the first study in Afghanistan conducted using long-term precipitation data collected from the observatory and SPI–RRV based on the change point analytical method.

The main objectives of the study were (a) to estimate the SPI-based meteorological drought to understand the magnitude and frequency of the drought, (b) to identify the change point for analyzing the temporal variation of drought risks based on the severe drought event, and (c) to analyze the spatial–temporal variation of precipitation trend using Mann–Kendall and Sen’s slope tests based on change point method, and (d) to quantify the spatial and temporal variations of sustainability of river basins using SPI–RRV concept and change point method.

**STUDY AREA**

Afghanistan, a country surrounded by mountains and other countries, is located within Central Asia’s southwest area. It shares an international boundary with Uzbekistan, Tajikistan, and Turkmenistan in the north; Iran in the west; Pakistan in the southeast; and China in the northeast. The country has a total area of 652,000 km². Its geographic location 29°–39° N, 60°–75° E. Its landscape is significantly undulating, with 75% occupied by mountains. The population of the country is 34 million, of which 70% live in rural areas (Zhiltsov et al., 2018). Afghanistan has a subtropical and continental climate with hot sunny summer and cold, relatively rainy winter. According to the Köppen–Geiger climate classification, the country’s climate zones are arid desert, arid steppe, temperate dry summer, cold, dry summer, and polar tundra. Moreover, variations in rainfall are extensive and differ according to altitude. The southern part of the country is arid and covered mainly by desert. The far east receives moderate rain even during summer due to the part effects of the Indian monsoon. The average temperature in January is 0–8°C, with absolute minimum temperature ranging from −20 to −25°C. The average temperatures in July on the plains range from 24 to 32°C with a 45°C absolute maximum temperature (Qutbudin et al., 2019). The entire country is divided into five major river basins (Fig. 1), namely Amu Darya, Harirud-Murghab, Helmand, Northern, and Kabul (Indus) river basins having areas of 96,599 km², 77,595 km², 327,801 km², 70,914 km², and 72,685 km², respectively (World Bank 2018). The World Bank report (2018) mentioned that the annual average rainfall is about 327 mm, and from the report of 2007, 58% of the total area is exploited for agricultural activities.

According to the European Asylum Support Office (EASO) (2020), the growth rate of the Afghan economy was from an average of 9% between 2003 and 2013 and fell to 2.7% in 2014 and 1.5% in 2015. The economic growth then recovered in 2016 and 2017 but slowed down to 1.8% in 2018 due to severe drought and political uncertainty. The adverse regional economic or political influences have impacted Afghanistan negatively through reducing remittance flows, heavily increased returnees, and displacement. The report has also mentioned that the country’s economy and institutions remained under pressure due to the high number of IDPs and returnees, COVID-19, and natural disasters such as droughts, floods, and earthquakes. The population growth and the lack of quality education and investments further prevented Afghanistan’s development.

According to World Bank (2018), efforts have been initiated to maintain the hydrological and meteorological records in Afghanistan only after 1940 and in the middle of 1950. After that, the system of hydrometric expanded quickly in the 1960s and in the 1970s. There was a maximum of 150 stations installed in the year 1980. However, the instability due to the local war resulted in decrease in public assets.

Afghanistan has 34 provinces, according to a World Bank report based on the National Statistics and Information Authority (NSIA) survey of 2017. The five provinces with high population in the country are as follows excluding nomadic population. Kabul province, located in the Kabul river basin, has a population of 4,523,718, from which 15.1% live in rural areas. Herat province, situated in the Harrirud river basin, has a population of 1,928,327, of which 70.9% live in rural areas. Nangarhar province, located in the south of the Kabul river basin, has a total population of 1,545,448, of which 84.6% reside in rural areas. Balkh province is in the northern river basin and it has a population of 1,353,626, and 62.7% live in rural areas. Kandahar province, located in the Hilmand river basin and it has a population of 1,252,786, of which 64.2% reside in rural areas. According to a World Bank report based on the FAO survey 2010, the five provinces
that have large agricultural areas of 8232 km², 5641 km², 5497 km², 5114 km², and 4362 km² are Herat in Harrirud river basin, Faryab, and Balkh at northern river basin, Takhar in Amu river basin and Kandahar at Helmand river basin, respectively. Also, the World Bank report based on Agriculture and Livestock Coverage based on districts Source (ALCS) survey of 2016–2017 revealed that high percentages of households whose primary income sources are from agriculture and livestock.

**METHODOLOGY**

The methodology includes the statistical test on precipitation data, trend analysis, and RRV concept linked with SPI based on the change point analysis. Statistical tests, such as correlation analysis, were performed on the precipitation data of each station to its spatially averaged mean value. The data were used further to analyze precipitation trends using Mann–Kendall and Sen’s slope tests for spatial–temporal variation. The SPI was analyzed to determine drought characteristics such as drought duration, frequency, number of times the drought occurred, and magnitude. Following that, the spatial–temporal variations of sustainability using the RRV concept as described by Ahmed et al. (2019a, b) and Sediqi et al. (2019) were analyzed. Temporal variation was analyzed using significant change points identified based on severe drought years, and accordingly, the sustainability was estimated. Finally, spatial–temporal variations were mapped for precipitation trend, RRV indicators, and precipitation sustainability. The flowchart describing the proposed methods is presented in Figure 2.

**Description of the Data**

The historical monthly precipitation data from 23 gauging stations were obtained from the Ministry.
of Water and Energy (MWE), Afghanistan with complete records of around 47 years (1970–2016). As these stations cover almost all the five river basins and are uniformly spread across the country, the results of the study can be considered very comprehensive. The data were arranged as annual precipitation, and the stations were categorized based on basin level and the locations are marked in Figure 1.

Raster maps of Afghanistan’s international and major river basin boundaries were used for spatial mapping. To better understand the changes in indicators, an investigation of spatial–temporal variation and sustainability of water resources is necessary. The information is required for different locations for the detailed analysis, mainly covering larger region. This study presents the variations in precipitation trend, RRV indicators, and precipitation sustainability of each of the grid points processed in ArcGIS 10.4 for preparing the respective maps.

**Drought Estimation from SPI**

Drought characteristics were investigated by SPI having a certain duration (typically 12 months) as described by (McKee et al. 1995; Sirdas et al. 2003). The SPI indicates a point’s distance from and in what direction it diverges from the distribution’s average. The SPI is negative at the time when a deficit occurs. The precipitation data were taken based on the time series of the records as \(X_1, X_2, X_3, \ldots, X_n\), are truncated in the threshold rainfall value, \(X_0\) (the axis that divides dry and wet years which has zero SPI values). Hence, drought is considered based on evaluating the time series of a given rainfall with the threshold value. When each value of the time series in the \(i\)th moment is largely related to the threshold altitude, then wet spell will occur \((X_i > X_0)\). Otherwise, a dry spell takes place \((X_i < X_0)\). A high value of water shortage during all periods of drought results in drought severity. The SPI was used for representing different levels of meteorological drought severity according to McKee et al. (1995). SPI has four categories for defining the severity of drought, such as: mild when the minimum SPI is between 0 and \(-1\); moderate, when \(-1.5 < \text{SPI} < -1\); severe when \(-2 < \text{SPI} < -1.5\); and extreme droughts where SPI \(< -2\). During the dry period, the accumulated amount of deficits is called as drought magnitude. The sum of approximate values of SPI of all years in the drought event is called as drought duration. The drought episodes or drought number can include more dry years when the graph is started below the \(X_0\) and until it reaches \(X_0\) it is called as drought number.

![Flowchart describing the proposed methods.](image)
This analysis investigates drought characteristics (drought duration \((D)\), numbers \((D_n)\), and magnitude \((M)\)) using SPI, which is equal to standardization as:

\[
SPI_i = \frac{X_i - \bar{X}}{\sigma_x}
\]  

(1)

where \(\bar{X}\) is arithmetic average and \(\sigma_x\) is standard deviation for a time series. Drought characteristics are investigated by averages of 12 months. The time variation or temporal drought characteristics are estimated using a run analysis method. The drought magnitude for a station, \(M_j\), is obtained as:

\[
M_j = \sum_{i=1}^{m} |X_0 - SPI_i|
\]  

(2)

whether \(m\) denotes the value of deficits through the drought episode, and \(X_0\) is a standardized truncation value for each drought, which is equal to zero. On the other hand, actual drought magnitude \(M_{jr}\) in millimeter should be estimated for each station as:

\[
M_{jr} = M_j \sigma_M + \bar{X}_M
\]  

(3)

where \(\sigma_M\) and \(\bar{X}_M\) represent standard deviation and arithmetic mean, respectively. Drought characteristics are analyzed for all the stations in the truncated diagrams (Fig. 3) to select change points related occurrence of severe drought in all of the country. The change points separate data series from all the stations in two periods (before change point and after change point). The selection of the overlap period is based on when the SPI graph started to decrease and reached severe drought; after that, the graph regains normal (Fig. 4). The period shows critical drought duration, as reported by World Bank (2018). Moreover, the SPI values per station are analyzed using multi-thresholds (for periods before and after change points, overlap periods, and all the series) to determine drought characteristics for calculating the temporal variation of sustainability using the SPI–RRV concept. Figure 4 presents the change point diagram of the temporal interval to calculate drought characteristics.
Spatiotemporal Variation of Precipitation Trend

The correlation coefficient for each rain gauge station \((X_i)\) with respect to the spatial mean \((X_j = \sum_{i=1}^{n} X_i)\) was computed. The trend analysis for the precipitation data was conducted using the collected data (Chen et al. 2009). The slope of the trend based on the change point was calculated for all the stations across the river basins. The precipitation trend was analyzed using non-parametric statistical tests, namely Mann–Kendall and Sen’s slope tests (Chen et al. 2009). The trend of the meteorological droughts or dry spells based on the change point was adopted to determine the long-term temporal changes. Also, the Mann–Whitney–Pettitt (MWP) technique developed by Pettitt (1979) was used for approximating significance probability \(p(t)\) as presented in Table 2. In this study, the significant change point was selected from the SPI truncation level. The minimum SPI was chosen as the change point of the station. The precipitation trend was analyzed temporally before and after the significant change point, also for overlapping the point and all the series (Fig. 4).

Spatiotemporal Variations of Sustainability using the RRV Concept

The sustainability indicator describes the consistency of available water resources over a longer period. Please note that, in this paper, we used the concept of sustainability only relating to the precipitation without including catchment characteristics. It is a function of reliability, resiliency, and dimensional vulnerability indicators (Ahmed et al. 2014; Lu et al. 2019; Sedigi et al. 2019; Shiru et al. 2021). Reliability means reducing the number of occurrences of droughts from normal situations,
ranging from zero to one. There is no drought if the value is one; otherwise, any value less than one indicates an increase in occurrences of drought. The quantitative value of the reliability indicator can be denoted as:

\[ \text{Reliability} = 1 - \frac{\sum_{i=1}^{n} D_i}{N} \]  

(4)

where \( N \) is the number of years in a site, and \( D \) is drought duration at \( (i) \) drought number series in a site.

The resiliency indicator illustrates the regaining possibility of improving and overcoming the drought to the normal level. The indicator shows relationships between drought duration and drought numbers. The resiliency indicator becomes one if the total drought duration and drought numbers are equal. It indicates that drought will quickly regain to the normal years (the droughts are for the short term). Most of the time, total drought duration is higher than drought numbers. Regardless of whether total drought duration increases and drought numbers decreases, if the resiliency indicator decreases, the drought is not regained to the normal year and would lead to long-term drought. The resiliency indicator can be calculated as:

\[ \text{Resiliency} = \left[ \frac{\sum_{i=1}^{n} D_i}{\sum_{i=1}^{n} (D_n)^{1/2}} \right]^{-1} \]  

(5)

where \( D_n \) represents drought numbers.

Vulnerability is a measure of the magnitude or amount of the event, estimated relating to the severity of the drought. The vulnerability indicator describes the relationships between total drought magnitude or precipitation deficit and drought numbers. Increasing total drought magnitude and decreasing drought numbers will increase vulnerability indicators. It means that drought intensity is increased. Decreasing in value of vulnerability illustrates that drought will be moderate and mild. The indicator can be derived as:

\[ \text{Vulnerability} = \frac{\sum_{i=1}^{n} M_i}{\sum_{i=1}^{n} (D_n)^{1/2}} \]  

(6)

where \( M \) is drought magnitude or precipitation deficit (mm).

Moreover, dimensionless vulnerability as an independent variable of sustainability is the proportion of vulnerability and demand. The demand is calculated from the mean annual precipitation (MAP). Also, dimensionless vulnerability can be calculated from the proportion of average precipitation deficit and MAP. The dimensionless value is calculated as:

\[ \text{Dimensionless vulnerability} = \frac{\sum_{i=1}^{n} M_i}{\sum_{i=1}^{n} (D_n)^{1/2}} \]  

(7)

Vulnerability is limited between MAP and zero. If the vulnerability is equal to MAP, then its dimensionless value is one. In such a case, the sustainability will be zero; otherwise, the dimensionless value is decreased with decrease in vulnerability indicator. In this condition, sustainability would increase. Sustainability is considered as a function of resiliency, reliability, and vulnerability indicators. It is calculated as (Shiru et al. 2021):

\[ \text{Sustainability} = |\text{Reliability} \times \text{Resiliency}(1 - \text{Dimensional vulnerability})| \]  

(8)

This study considered the indicators throughout drought characteristics based on change points in each station.

The sustainability using RRV indicators is estimated based on spatial and temporal variation of droughts across all the stations. The RRV and sustainability indicators are estimated before and after change points for all the series (Fig. 4). The relative increase or decrease (denoted as percentage variation) of selected indicators that result after the change point was estimated relating to the values before the change point, thus:

\[ \text{Change in indicator(%) =} \frac{\text{Indicator after change point} - \text{indicator before change point}}{\text{Indicator after change point}} \times 100 \]  

(9)

Furthermore, we also computed the RRV and sustainability indicators using the entire data to verify the overall impacts of drought on the river basin.

RESULTS

Analysis of Drought Characteristics using SPI

The SPI with negative values specified that precipitation is less and consistently deviates from the mean value for a significant time. In this study, we analyzed SPI using the data collected from dif-
different stations located in the major river basins in Afghanistan (Fig. 5). The lowest values of SPI were found in 1970, 1971, 1984, 1985, 2000, 2001, 2008, and 2010 in all river basins (Fig. 5) and are presented in Table 1. Moreover, it was found that severe to moderate drought with long duration occurred in 2000 and 2001 in several of the stations. Based on this, the years 2000 and 2001 were fixed as the change points.

In most of the stations, it was found that the minimum SPI values correspond to moderate drought that started from 1993 and reached severe drought in 2000 and 2001. Further, the severity reduced to normal in 2005. However, the drought was very persistent across all the river basins in the years 2000 and 2001 (Fig. 5). Based on this, the overlap period was selected from 1993 to 2005. Further analysis for understanding the precipitation behavior against drought in terms of sustainability was conducted, separating the dataset into three such as (a) the data fall between 1970 and the change point (2000 or 2001), (ii) change point to 2016, (iii) overlap period (1993–2005) to examine when exactly critical droughts have occurred in all the stations. Moreover, drought characteristics such as number of drought events ($D_n$), duration ($D$), and magnitude ($M$) were estimated from the SPI (Fig. 3). In this study, drought characteristics and MAP were calculated separately in each of the sections (Fig. 4) to estimate the catchment sustainability against the drought both spatially and temporally.

**Spatiotemporal Variation of Precipitation Trend**

The correlation coefficient for each rain gauge station with respect to spatial mean was computed (Fig. 6). It is evident that the correlation largely varied between 0.44 and 0.96 across the basins. Less correlation was found in Faizabad, Farah, and Lashkargah. It is on the southwestern plateau, and the northern plains are arid with hot summers. High correlation was found in the center and southeast regions, including the stations (Lal-Sarjangal, Gardandiwal, Karizimir, Pul-i-Shark, Ghazni, Tang-i-Sayedan, KhwajaRawash, Khost, North Salang). These areas are located mainly in the central highland semiarid with cold winters.

Precipitation trends by the Mann-Kendal and Sen’s slope tests were estimated for the data collected from five major river basins. Table 2 shows the MAP for each of the stations, the probability of change points (pt) found in different years, precipitation slope estimated before and after change points, overlap (1993–2005), and the entire period (1970–2016). The MAP has low and high values of 150 mm and 689 mm, in Lashkargah and Jalalabad stations, respectively. The minimum $p(t)$ value was 0.2 at Ghalmin station, while the high-value was 1 in all the stations located in the central part of the country. The $p(t)$ values increased with increasing precipitation in most of the stations. Because the $p(t)$ value is a function of the Mann-Kendal statistic value, and because the statistic value increased when more positive changes occurred in annual precipitation, increasing the $p(t)$ value shows high positive trend in rainfall.

The significant change point (Fig. 4) was determined per station, and these points were selected based on the more severe and long period of drought. All the stations showed severe drought for a long period in 2000 and 2001, but in the Sheberghan station, the severe drought occurred in 1996. In this study, the severe drought years were selected based on minimum SPI having a value less than – 1.5. The high precipitation slope from 1970 to change points was 4.62 mm/year in Tang-i-Sayedan station, while many stations exhibited positive slopes indicating the increase in precipitation. On the contrary, stations such as Adraskan, Maimana, Herat, Ghalmin, and Qadis exhibited negative slopes indicating a decrease in precipitation. Moreover, the slopes between change points and 2016 showed positive value in all the stations. A steep slope of 34.64 mm/year was found in Jalalabad, and a gentle slope of 0.36 mm/year resulted in Qadis station. The slopes in this section showed that precipitation increased rapidly after change points in all the stations. Moreover, the trends of the overlapping period from 1993 to 2005 showed negative values, which means that precipitation decreased in this period in all the stations. However, the stations such as Faizabad, Shibergan, Maimana, and Qadis showed a recovery from the drought during the period. Finally, the slopes estimated using the complete dataset (i.e., 1970–2016) were negative in Kandahar, Adraskan, Lashkargah, Farah, Herat, and Qadis stations, which are located in the west of the country and have an arid climate. In contrast, other stations that are located in central and east parts of the country showed positive trends.

The precipitation trends (Table 2) were spatially and temporally mapped (Fig. 7). Figure 7a illustrates the precipitation trend (PT) from 1970 to
change points, the trend varied between – 2.6 and 4.6 mm/year. The red color explains the area of negative trends in the northwest of the country, which meant that precipitation decreased in the north of Hilmand and Harrirud-Murghab river basins. The map shows an increasing trend toward the center and southeast of Afghanistan. Moreover, Figure 7b spatially explains PT from change points to 2016. The trends ranged between 0.37 and 35 mm/year. The west part of Hilmand, Harrirud-Murghab, and north of the Northern river basins showed a low trend and increases to the east of Hilmand and

Figure 5. SPI estimated for the five river basins.

Figure 6. Correlation coefficient of precipitation with respect to spatial mean.
southeast of Amu and Kabul river basins. Then, Figure 7c shows spatial variation of PT from 1993 to 2005 for overlapping the change point. The trend ranged between \(9.5 \text{ mm/year}\) and the negative trends confirmed the decrease in precipitation. In this period, the positive trend resulted in one rain gauge station of Amu and north parts of the Northern and Harrirud-Murghab river basins. A low value of PT, i.e, \(9.5 \text{ mm/year}\), was observed in the west of Hilmand and it increased to the east and north of the country. In addition, Figure 7d explains PT from 1970 to 2016. The trends ranged between \(1.4 \text{ and 6 mm/year}\). West of Hilmand and Harrirud-Murghab river basin showed negative trends, while east of the basins showed positive trends and increased to Northern, Amu, and Kabul river basins.

### Spatiotemporal Variation of Drought using RRV Concept

In the following sections, RRV and sustainability indicators were used to characterize the impacts of drought. Detailed estimates of reliability, resiliency, vulnerability, and sustainability were made to visualize the impacts spatially and temporally with respect to the change point.

#### Spatiotemporal Variation of Reliability

Table 3 presents the reliability index for all the river basins of Afghanistan with respect to the change point against the drought. All the stations in the Harrirud–Murghab river basin resulted in increase in reliability. Although it looks very positive, it does not have much impact on the socio-economic activities mainly because of the remote location and less population. It may also be noted that the Harrirud–Murghab river basin receives less rainfall than other basins. All the other river basins showed both positive and negative percentage changes in reliability. The positive change was predominant in many of the stations. The highest 29\% change in reliability was found in the Shiberghan station of the northern river basin, and lowest positive change of 4\% was

| River basins     | Stations          | MAP (mm) | \(P(t)\) | Change points | Precipitation trend (mm/year) |
|------------------|-------------------|----------|-----------|---------------|-----------------------------|
|                  |                   |          |           |               | 1970-Change point | Change point-2016 | 1993–2005 | 1970–2016 |
| Hilmand          | Kandahar          | 198      | 0.39      | 2000          | 1.73                       | 3.3                   | – 3.33    | – 0.6     |
|                  | Gardandiwal       | 493      | 1.00      | 2001          | 2.66                       | 19.14                 | – 1.22    | 3.44      |
|                  | Adraskan          | 228      | 0.75      | 2001          | – 1.46                     | 1.82                  | – 2.81    | – 1.37    |
|                  | Lashkargah        | 150      | 0.87      | 2001          | 0.23                       | 1.03                  | – 7.88    | – 1.2     |
|                  | Farah             | 152      | 0.91      | 2001          | 0.03                       | 1.57                  | – 9.34    | – 1.4     |
|                  | Ghazni            | 451      | 0.99      | 2000          | 3.35                       | 19.52                 | – 2.33    | 3.31      |
| Kabul            | KhwajaRawash      | 505      | 1.00      | 2001          | 2.77                       | 17.82                 | – 1.65    | 3.99      |
|                  | Pul-i-Surkh       | 491      | 1.00      | 2000          | 3.2                        | 20.45                 | – 0.59    | 4.02      |
|                  | Tang-i-Sayedan    | 563      | 1.00      | 2000          | 4.62                       | 23.95                 | – 1.05    | 5.1       |
|                  | Karizim           | 484      | 1.00      | 2000          | 3.83                       | 20.25                 | – 1.23    | 3.81      |
|                  | Khost             | 595      | 1.00      | 2000          | 3.26                       | 26.96                 | – 4.66    | 4.67      |
|                  | Jalalabad         | 689      | 1.00      | 2000          | 3.89                       | 34.64                 | – 2.55    | 6         |
|                  | Faizabad          | 522      | 0.70      | 2001          | 0.48                       | 8                     | 0.17      | 1.07      |
| Amu Darya        | Kunduz            | 335      | 0.90      | 2001          | 1.44                       | 6.31                  | – 0.83    | 1.41      |
|                  | Baghlan           | 349      | 0.94      | 2001          | 1.72                       | 7.1                   | – 2.1     | 1.56      |
|                  | North Salang      | 547      | 0.99      | 2001          | 1.82                       | 16.99                 | – 0.17    | 3.15      |
|                  | Shiberghan        | 208      | 0.70      | 1996          | 1.03                       | 1.38                  | 0.53      | 1.07      |
| Northern         | Maimana           | 281      | 0.90      | 2000          | – 0.9                      | 2.12                  | 3.8       | 1.41      |
|                  | Mazar-i Sharif    | 242      | 0.94      | 2001          | 1.36                       | 3.95                  | – 2.47    | 1.56      |
| HarrirudMurghab  | Herat             | 236      | 0.35      | 2001          | – 1.67                     | 1.83                  | – 1.44    | – 1.28    |
|                  | Ghalmin           | 337      | 0.02      | 2001          | – 0.58                     | 1.61                  | – 2.13    | 0.22      |
|                  | Lal-Sarjangal     | 349      | 0.89      | 2001          | 0.48                       | 9.56                  | – 2.39    | 1.69      |
|                  | Qadis             | 272      | 0.55      | 2001          | – 2.57                     | 0.36                  | 3.85      | – 0.97    |
noted from the Pul-i-Surkh, Tang-i-Sayedan, Karizmir stations of the Kabul river basin. Overall, Kabul river basin produced mixed reliability ranges between the highest of 25% (Jalalabad Station) to the lowest of 11% (KhwajaRawash station). Kabul is a densely populated region, and any negative impact of drought will have significant impact on the socio-economic conditions of the country.

Figure 8 shows the spatial variation of reliability across all the river basins before and after the change point. It can be seen from the figure that low reliability was dominant in the east of the Harrirud and some parts of Hilmand and northern river basins. However, high reliability can be seen in the northeast and southeast of the country. The overall analysis of reliability indicators showed that, before the change points, it ranged between 0.44 and 0.51, whereas after the change point, it slightly increased in the upper region (i.e., 0.44–0.65). The slight increase in reliability can be taken as positive. However, the reduction in reliability needs careful further investigation. The reliability was also computed by taking the entire data (i.e., 1970–2016) and different indicators were found for results before and after the change point.

**Spatiotemporal Variation of Resiliency**

The resiliency computed before and after the change point for the selected river basins is presented in Table 4. The increase in resiliency indicates the precipitation pattern to bring into the original state. This is accomplished mainly with consistent precipitation over the long period after the severe drought. The results obtained revealed...
that, except Kabul river basin, all the other basins’ resiliency showed a positive percentage change. The positive shift in resiliency against the drought is highly desirable to ensure the region’s water security. However, the negative resiliency of the Kabul river basin resulted from almost all the stations except Jalalabad, which supports the significant decrease in precipitation that continued after the change point.

The spatial and temporal variations of resiliency indicators are illustrated in Figure 9. From this figure, it is clear that the spatial variation of resiliency before change points varied between 0.38 and 0.5. In addition, the upper range increased drastically to 0.75 after the change point. However, the lower range reduced to 0.33, which is alarming and needs further introspection. Figure 9c confirms the finding of low resiliency (red color) of a major part of the Kabul river basin. Similar to reliability, the resiliency computed using the entire data was different from the results of before and after the change point.

Table 3. Estimated reliability of the river basins

| River basins | Stations       | Change points | Reliability indicators |
|--------------|----------------|---------------|------------------------|
|              |                | 1970-Change point | Change point-2016 | Changed by % |
| Kabul        | KhwajaRawash   | 2001          | 0.48                  | 0.44      | – 11 |
|              | Pul-i-Surkh    | 2000          | 0.45                  | 0.47      | 4   |
|              | Tang-i-Sayedan | 2000          | 0.45                  | 0.47      | 4   |
|              | Karizimir      | 2000          | 0.45                  | 0.47      | 4   |
|              | Khost          | 2000          | 0.52                  | 0.59      | 12  |
|              | Jalalabad      | 2000          | 0.48                  | 0.65      | 25  |
| Amu Darya    | Faizabad       | 2001          | 0.38                  | 0.44      | 14  |
|              | Kunduz         | 2001          | 0.47                  | 0.50      | 6   |
|              | Baghlan        | 2001          | 0.50                  | 0.50      | 0   |
|              | North Salang   | 2001          | 0.59                  | 0.50      | – 19 |
| Northern     | Shiberghan     | 1996          | 0.48                  | 0.57      | 16  |
|              | Maimana        | 2000          | 0.42                  | 0.59      | 29  |
|              | Mazar-i Sharif | 2001          | 0.53                  | 0.50      | – 6  |
| HarirudMurghab | Herat       | 2001          | 0.44                  | 0.50      | 13  |
|              | Ghalmin        | 2001          | 0.41                  | 0.56      | 28  |
|              | Lal-Sarjangal  | 2001          | 0.44                  | 0.56      | 22  |
|              | Qadis          | 2001          | 0.44                  | 0.56      | 22  |

Spatiotemporal Variation of Vulnerability

The vulnerability indicators calculated from the selected river basins are summarized in Table 5. The negative percentage change of vulnerability after the change point indicates that the vulnerability against the drought is decreasing. On the other hand, the positive percentage change indicates an increase in vulnerability. Having mentioned that, most of the river basins were improving against vulnerability after the severe drought that occurred in 2000. With regards to vulnerability assessment, the Hilmand river basin resulted in high negative percentage of change in vulnerability (highest being minus 82%) almost in all stations compared to other river basins. The positive percentage change of vulnerability is
highly noted in the Kabul river basin where it ranged between 15 and 33%. This supports the results presented in the previous sections that demonstrate the less reliability and resiliency of the Kabul river basin. After the Kabul river basin, the northern river basin showed a positive percentage change in vulnerability but relatively having less values. This river basin, however, might progress to be highly vulnerable to drought in the future.

The spatial variability of vulnerability and the progress after the change point is further illustrated in Figure 10. It is worth noting that the overall range of vulnerability estimated from all the river basins was 0.26–0.8. However, this got significantly reduced to 0.2–0.57. This result supports the fact that the vulnerability indicator decreased after the change point. The vulnerability threatens the water resources in the east of the Hilmand, part of the Kabul, and south of the Amu river basins (please refer to the positive percentage change in Fig. 10c). The vulnerability estimated using the entire data (1970–2016) is not similar to results before and after the change point vulnerability.

Spatiotemporal Variation of Sustainability

Table 6 summarizes the sustainability indicators calculated from the selected river basins. Most river basins yielded a positive value of percentage change of sustainability after the change point. However, negative percentage change was consistent across all the selected stations of the Kabul river basin except Jalalabad. Like the impacts of other indicators, the negative percentage change of sustainability in the Kabul river basin can be considered severe (−4 to

Figure 8. Maps of spatiotemporal variations of reliability in Afghanistan.
Similar behavior can also be observed in the North Salang station of the Amu river basin. This is mainly due to closely sharing the boundary with the Kabul river basin. The stations Ghazni and Gardandiwal of the Hilmand river basin also showed a negative percentage change in sustainability after the change point.

The percentage change of spatial variability of sustainability is illustrated in (Fig. 11) before and after the change point. The sustainability range before the change point was 0.33–0.56. However, a larger range was found after the change point 0.41–0.66, which is an encouraging remark on the sustainability perspective considering the entire basin of the country. However, the red color, as depicted in Figure 11c, clearly indicates the reduction in the sustainability in the Kabul river basin and other river basins that share the boundary. Similar to all three previous indicators, the sustainability estimated from the complete dataset is not consistent with the results obtained using the data of before and after the change point.

**DISCUSSION**

In the present study, the SPI–RRV concept coupled with the change point method was developed to analyze the spatiotemporal variation of sustainability of available water resources and thus to demonstrate how the river basin of Afghanistan behaves against drought risks. The analysis resulted in spatiotemporal variations of RRV and sustainability indicators, which are essential information for the drought monitoring program and to define drought forecasts related information for decision making.

Estimating drought occurrence and frequencies are necessary to understand droughts’ structure better. While SPI is flexible and can be applied on different time scales, this study used the long-term...
12 months SPI values with the intention of bringing a strong relationship with the hydrologic variables such as streamflow, groundwater, and reservoir storage (Hong et al. 2015). Furthermore, the alteration of a process from a stable state to another stable state in hydro-climate can be defined as a significant change in a statistical characteristic. We found from the results that several severe droughts in most stations occurred in different years, as shown in Figure 5 and Table 1. However, almost all the river basins experienced severe drought in the years 2000 and 2001. The drought in these years was also mentioned in World Bank Report (2018) as the critical drought in Afghanistan, and thus the years 2000 and 2001 were fixed as change points for further analysis.

As illustrated in Figure 6, the large spatial variation was induced mainly because of complex weather patterns, atmospheric interactions, Indian monsoons, movement of wind direction, the topography of the county (Qutbudin et al. 2019). While trend analysis of annual precipitation of Afghanistan has been reported in Sedigi et al. (2019), this study improved the precipitation trend analysis by using the change point method and multiple data stations, which are suitable for the area that has high precipitation variations. The precipitation trends before and after the change point were drastically dissimilar to the trend of all the series (Fig. 7). The trend of the overlapping period on the change point was negative from 1993 to 2005, which affected the trend of all series. However, fixing the change point and performing the entire analysis before and after the change point clarified that trends are increasing more after the change points in all the stations.

The RRV indicators generally estimate sustainability in water resources, which is the major component of economic development and

Figure 9. Maps of spatiotemporal variations of resiliency in Afghanistan.
improvement of human wellbeing (Shiru et al. 2021). For evaluating the spatial and temporal changes of water resources sustainability for Afghanistan river basins during the periods 1970–2001 and 2001–2016, as well as for 1970–2016, the data collected from 23 data stations were used. The investigation estimated temporal variations of the indicators in various time scales. Owing to the highly undulated topography of Afghanistan, a largely varying pattern of changes in the indicators were found both spatial as well as temporal. The percentage of temporal variations after the change point showed that Kabul river basin produced mixed reliability ranges between the highest of 25% (Jalalabad Station) to the lowest of -11% (KhwajaRawash station) as shown in Table 3. Moreover, after the change point, the resiliency reduced from 7 to 44% in most of the stations in the southeast and center of Afghanistan, as shown in Table 6 and Figure 11c. The slight increase in sustainability can be taken as positive. However, the reduction in sustainability needs careful further investigation in several regions of the country. However, the temporal variations in sustainability of water availability were found to be facing the impacts of climate change. The water availability further suffered due to a decrease in precipitation; also, it might get affected by direct and indirect human actions (Shiru et al. 2021). As the Kabul is a densely populated region that also exists in the drought affected area, and the major source of water to Hilmand, Harrirud, and Northern river basins, any negative impacts of drought on the region will have significant impacts on the socio-economic conditions of the country.

Overall, the sustainability showed that after the change point, it decreased in the southeast and center and it increased in all other regions of the country. The results from this study corroborate to findings of previous studies (e.g., Caloiero et al.,

### Table 5. Estimated vulnerability of river basins

| River basins | Stations      | Change points | Vulnerability indicators | 1970-Change point | Change point-2016 | Changed by % |
|--------------|---------------|---------------|--------------------------|-------------------|-------------------|--------------|
| Hilmand      | Kandahar      | 2000          |                          | 0.80              | 0.44              | - 82         |
|              | Gardandiwal   | 2001          |                          | 0.44              | 0.49              | 9            |
|              | Adraskan      | 2001          |                          | 0.59              | 0.38              | - 56         |
|              | Lashkargah    | 2001          |                          | 0.67              | 0.37              | - 82         |
|              | Farah         | 2001          |                          | 0.50              | 0.40              | - 25         |
|              | Ghazni        | 2000          |                          | 0.44              | 0.56              | 21           |
| Kabul        | KhwajaRawash  | 2001          |                          | 0.46              | 0.40              | - 15         |
|              | Pul-i-Surkh   | 2000          |                          | 0.40              | 0.52              | 24           |
|              | Tang-i-Sayedan| 2000          |                          | 0.42              | 0.49              | 15           |
|              | Karizimir     | 2000          |                          | 0.38              | 0.57              | 33           |
|              | Khost         | 2000          |                          | 0.34              | 0.48              | 30           |
|              | Jalalabad     | 2000          |                          | 0.33              | 0.49              | 33           |
| Amu Darya    | Faizabad      | 2001          |                          | 0.26              | 0.20              | - 34         |
|              | Kunduz        | 2001          |                          | 0.37              | 0.25              | - 48         |
|              | Baghlan       | 2001          |                          | 0.45              | 0.27              | - 70         |
|              | North Salang  | 2001          |                          | 0.36              | 0.41              | 13           |
| Northern     | Shiberghan    | 1996          |                          | 0.29              | 0.29              | 1            |
|              | Maimana       | 2000          |                          | 0.29              | 0.32              | 9            |
|              | Mazar-i Sharif| 2001          |                          | 0.33              | 0.31              | - 8          |
| HarirudMurghab | Herat       | 2001          |                          | 0.52              | 0.31              | - 64         |
|              | Ghalmin       | 2001          |                          | 0.42              | 0.31              | - 38         |
|              | Lal-Sarjangal | 2001          |                          | 0.49              | 0.49              | 0            |
|              | Qadis         | 2001          |                          | 0.65              | 0.37              | - 77         |
which showed a generally decreasing trend in the precipitation and increasing aridity (Ahmed et al., 2019a, b; Pour et al., 2019) in the Central Asia region (Qutbudin et al., 2019; Sediqi et al. 2019) in Afghanistan. In contrast, the aim of the present study was not just to show the trend analysis of precipitation. Instead, the main focus was to show how the river basin behaved against the drought risks individually. The results can be used to make any policy-level changes in the country to better adapt to the future worst droughts.

**SUMMARY AND CONCLUSION**

The study was conducted to quantify the spatial and temporal variation of sustainability in response to meteorological droughts. The historical annual precipitation data with complete records of 47 years from 23 rain gauge stations across the country were collected from MWE of Afghanistan. Initial statistical analyses such as Mann–Kendall and Sen’s slope tests were performed to estimate the trends that exist in the precipitation data. Further, meteorological droughts were computed for characterizing the droughts in terms of duration, numbers, and magnitude using the SPI. Identifying the correct
change point is important to show the overall relative increase/decrease in drought progression temporally. Based on the severity of the drought analyzed from precipitation of all the stations, the years 2000 and 2001 were fixed as a change point. Further, the RRV concept was used to quantify the sustainability of different river basins both spatially and temporally with reference to change points. From the trend analysis using the data before the change point, it was found that the trend ranges between $2.6$ and $4.6$ mm/year. The northwest regions of the country had negative trends, and the trend increased to a positive value toward the center and southeast of Afghanistan. However, an increase in the trend, such as $0.37$–$35$ mm/year, was found after the change point. This behavior was evident in the west and northwest of the country, having less trend and increased in the southeast part. While we could not draw significant findings from the analysis performed using the entire dataset, the overlapping period showed a significant negative precipitation trend. This behavior is quite apparent that the majority of the severe droughts occurred in the history of Afghanistan during the overlapping period (1993–2005).

Temporal variations after the change point, especially for reliability, resiliency, vulnerability, and sustainability, showed a positive impact in the majority of the river basins except for the upstream Kabul river and part of the Hilmand and Amu river basins that share the boundary with Kabul river basin. In the Kabul river basin, the maximum decrease in reliability, resiliency, and sustainability were $11, 24$, and $19\%$, respectively, whereas there is an increase in vulnerability of $33\%$. Despite the positive impacts of improving the sustainability of other river basins, the sustainability of the Kabul river basin suffered significantly. Thus, it needs greater attention to manage the negative impacts caused by climate change. As the country has a

| River basins | Stations | Change points | Sustainability indicators |
|-------------|---------|---------------|--------------------------|
|             |         |               | 1970-Change point | Change point-2016 | Changed by % |
| Hilmand     | Kandahar | 2000          | 0.32                    | 0.57               | 45          |
|             | Gardandiwal | 2001         | 0.49                    | 0.46               | 7           |
|             | Adraskan | 2001          | 0.43                    | 0.63               | 32          |
|             | Lashkargah | 2001        | 0.43                    | 0.58               | 26          |
|             | Farah    | 2001          | 0.54                    | 0.56               | 4           |
|             | Ghazni   | 2000          | 0.49                    | 0.44               | 10          |
| Kabul       | KhwajaRawash | 2001        | 0.46                    | 0.44               | 4           |
|             | Pul-i-Surkh | 2000         | 0.48                    | 0.42               | 15          |
|             | Tang-i-Sayedan | 2000      | 0.48                    | 0.43               | 11          |
|             | Karizimir | 2000          | 0.49                    | 0.41               | 19          |
|             | Khost    | 2000          | 0.57                    | 0.51               | 12          |
|             | Jalalabad | 2000         | 0.52                    | 0.55               | 5           |
| Amu Darya   | Faizabad | 2001          | 0.50                    | 0.58               | 14          |
|             | Kunduz   | 2001          | 0.50                    | 0.57               | 13          |
|             | Baghljan | 2001          | 0.47                    | 0.57               | 18          |
|             | North Salang | 2001     | 0.59                    | 0.48               | 23          |
| Northern    | Shiberghan | 1996         | 0.55                    | 0.65               | 14          |
|             | Maimana  | 2000          | 0.53                    | 0.66               | 20          |
|             | Mazar-i Sharif | 2001     | 0.55                    | 0.56               | 1           |
| HarirudMurghab | Herat    | 2001          | 0.45                    | 0.64               | 28          |
|             | Ghalmin  | 2001          | 0.44                    | 0.65               | 32          |
|             | Lal-Sarjangal | 2001      | 0.42                    | 0.50               | 15          |
|             | Qadis    | 2001          | 0.37                    | 0.63               | 41          |
complex topography, the effective management of water resources is critical to avoiding the shortage of future water and food crises.

AUTHOR CONTRIBUTIONS

The first and second authors have contributed equally to conceptualization, performing the analyses, investigation of results, and writing the manuscript.

FUNDING

This research received no external funding.

AVAILABILITY OF DATA AND MATERIALS

The data and codes will be shared upon the request.

DECLARATIONS

Conflict of Interest  The authors declare no conflict of interest.

REFERENCES

Ahmed, K., Shahid, S., Bin Harun, S., Ismail, T., Nawaz, N., & Shamsudin, S. (2014). Assessment of groundwater potential zones in an arid region based on catastrophe theory. *Earth Science Informatics, 8*, 539–549.
Ahmed, K., Shahid, S., Wang, X., Nawaz, N., & Khan, N. (2019a). Spatiotemporal changes in aridity of Pakistan during 1901–2016. *Hydrology and Earth System Sciences*, 23, 3081–3096.

Ahmed, K., Shamsuddin, S., Mehmet, C., Demirel, N. N., & Najeebullah, K. (2019b). The changing characteristics of groundwater sustainability in Pakistan from 2002 to 2016. *Hydrogeology Journal*, 27, 2485–2496.

Bazrafshan, J., Somayeh, H., & Jaber, R. (2014). Drought monitoring using the multivariate standardized precipitation index. *Water Resources Management*, 28, 1045–1060.

Benjamin, L., Hughes, M., & Saunders, A. (2002). A drought climatology for Europe. *Journal of Climateology*, 22(13), 1571–1592.

Brunner, I. M., Louise, S., Lena, M. T., & Martyn, C. (2021). Challenges in modeling and predicting floods and droughts. A review. *WIREs Water*, 10(1002), 1520.

Caloiero, T., Coscarelli, R., Gaudio, R., & Leonardo, G. P. (2019). Historical trends and variability of meteorological droughts in Taiwan. *Hydrological Sciences Journal*, 54(3), 430–441.

Chen, S. T., Kuo, C. C., & Yu, P. S. (2009). Precipitation trend and concentration in the Sardinia region. *Theoretical and Applied Climatology*, 107, 297–307.

Cannarozzo, M., Noto, L. V., & Viola, F. (2006). Spatial distribution of rainfall trends in Sicily 1921–2000. *Physics and Chemistry of the Earth, 31*, 1201–1211.

Chen, S. T., Kuo, C. C., & Yu, P. S. (2009). Historical trends and variability of meteorological droughts in Taiwan. *Hydrological Sciences Journal*, 54(3), 430–441.

Cr., P., Mihailescuc, I. F., Zoia, P., Carmen, D., Felicia, V., & Claudia, N. (2009). Combining the standardized precipitation index and climatic water deficit in characterizing droughts. A case study in Romania. *Theoretical and Applied Climatology*, 97, 219–233.

European Asylum Support Office (EASO) report. (2020). Key socioeconomic indicators Focus on Kabul City, Mazar-e Sharif and Herat City in Afghanistan. pp. 12–23.

Gabriel, C. B. (2011). Standardized precipitation index based on Pearson type iii distribution. *Revista Brasileira de Meteorologia*, 26(2), 167–180.

Gajbhiye, S., Meshram, C., Singh, S. K., Srivastava, P. K., & Islam, T. (2016). Precipitation trend analysis of Sindh River basin, India from 102-year record 1901–2002. *Atmos. Sci. Lett.*, 17, 71–77.

Golmohammadi, H. M., Hamid, R. S., Samuel, S., Solis, M., & Fooladi. (2021). Improving performance criteria in the water resource systems based on fuzzy approach. *Water Resources Management*, 35, 593–611.

Greetje, S., & Verena, B. (2015). The emergence of Southern standards in agricultural value chains. A new trend in sustainability governance? *Ecological Economics*, 120, 175–184.

Guttman, N. B. (1999). Accepting the standardized precipitation index. A calculation algorithm. *Journal of the American Water Resources Association*, 35, 593–611.

Hong, X., Guo, S., Xiong, L., & Liu, Z. (2015). Spatial and temporal analysis of drought using entropy-based standardized precipitation index: A case study in Poyang Lake basin. *China. Theoretical and Applied Climatology*, 122, 543–556.

Hosseini, A., Yousef, G., & Manuchehr, F. (2021). Characterization of drought dynamics in Iran by using S-TRACK method. *Theoretical and Applied Climatology*, 10, 1007.

Karavitis, A. C., Stavros, A., Demetrios, E. T., & George, A. (2011). Application of the standardized precipitation index (SPI) in Greece. *Water*, 3, 787–805.

Kundu, S., Ranjan, B., Ved, P., Gupta, H. S., Pathak, H., & Ladha, J. K. (2007). Long-term yield trend and sustainability of rainfed soybean–wheat system through farmyard manure application in a sandy loam soil of the Indian Himalayas. *Biology and Fertility of Soils*, 43, 271–280.

Lu, H., Kang, Y., Liu, L., & Li, J. (2019). Comprehensive groundwater safety assessment under potential shale gas contamination based on integrated analysis of reliability-vulnerability and gas migration index. *Journal of Hydrology*, 578, 124072.

Machiwal, D., Madan, K. J., & Ankit, G. (2020). Development of a rainfall Stability Index using probabilistic indicators. *Eco logical Indicators*, 115, 106406.

Mee, T. B., Doesken, N. J., & Kleist, J. (1993). The relationship of drought frequency and duration to time scales. In: *Eighth conference on applied climatology*. Anaheim, 17–22 January 1993, 179–184.

Mojid, M. A., Mohammad, F. P., Mohammed, M., & Geo, H. (2019). Water table trend—a sustainability status of groundwater development in North-West Bangladesh. *Water*, 11, 1182.

Pettitt, A. N. (1979). A nonparametric approach to the change-point problem. *Journal Royal Statistical Society*, 28(2), 126–135.

Pour, S. H., Wahab, A. K. A., & Shahid, S. (2019). Spatiotemporal changes in aridity and the shift of drylands in Iran. *Atmospheric Research*, 235, 104704.

Qiang, Z., Chong, Y. X., & Zhang, Z. (2009). Observed changes of drought/wetness episodes in the Pearl River basin, China, using the standardized precipitation index and aridity index. *Theoretical and Applied Climatology*, 98, 89–99.

Outbudin, I., Shiru, M. S., Sharafati, A., Ahmed, K., Al Ansari, N., Yaseen, Z. M., Shahid, S., & Wang, X. (2019). Seasonal drought pattern changes due to climate variability: Case study in Afghanistan. *Water*, 11, 1096.

Rasmusson, E. M., & Arkin, P. A. (1993). A global view of large-scale precipitation variability. *Journal of Climate*, 6, 1495–1522.

Roudak, C., Stephen, E. S., & Diogo, B. (2014). Time-dependent health risk from contaminated groundwater including use of reliability, resilience, and vulnerability as measures. *Journal of the American Water Resources Association*, 50(1), 14–28. https://doi.org/10.1111/jawr.12103.

Seddiq, M. N., Shiru, M. S., Nashwan, M. S., Shadan, R. A., Wang, A. X., Shamsuddin, K. A., Asaduzzaman, S. M., & Manawi, S. M. A. (2019). Spatiotemporal pattern in the changes in availability and sustainability of water resources in Afghanistan. *Sustainability*, 11, 5836.

Sergio, M. V., & Serrano. (2006). Evaluating the impact of drought using remote sensing in a Mediterranean, Semi-arid Region. *Natural Hazards*, 40, 173–208.

Sevinc, S., & Zekai, S. (2005). Spatio-temporal drought analysis in the Trakya region, Turkey. *Hydrological Sciences Journal*, 48(5), 809–820.

Shahid, S., Wang, X. J., Moshiur Rahman, M., Hasan, R., Harun, S. B., & Shamsudin, S. (2015). Spatial assessment of groundwater over-exploitation in northwestern districts of Bangladesh. *Journal of the Geological Society of India*, 85, 463–470.

Sharma, S., Kalhana, H., Nitesh, K., Dibas, S., Deepak, A., & Sudeep, T. (2021). Drought characteristics over Nepal Himalaya and their relationship with climatic indices. *Meteorological Applications*, 28, e1988.

Sheffield, J., Wood, E. F., & Roderick, M. L. (2012). Little change in global drought over the past 60 years. *Nature*, 491(435), 438.

Shiru, M. S., Shahid, S., & Park, I. (2021). Projection of water availability and sustainability in Nigeria due to climate change. *Sustainability*, 13, 6284.

Tommasso, C., Paola, C., & Francesco, F. (2018). Long-term precipitation trend analysis in Europe and in the Mediterranean basin. *Water and Environment Journal*, 32(1747–6585), 433–445.

Tsai, F.-T.-C., Vineet, K., Doug, T., & Robert, A. G. (2009). Conjunctive management of large-scale pressurized water distribution and groundwater systems in semi-arid area with
parallel genetic algorithm. *Water Resources Management, 23*, 1497–1517.

Valdes Abellan, J., Pardo, M. A., & Tenza Abril, A. J. (2017). Short communication observed precipitation trend changes in the western Mediterranean region. *International Journal of Climatology, 37*(1), 1285–1296.

World Bank Report. (2018). Strengthening hydromet and early warning services in Afghanistan. A road map, pp. 25–18.

Wu, H., Michael, J. H., Donald, A. W., & Mark, D. S. (2005). The effect of the length of record on the standardized precipitation index calculation. *International Journal of Climatology, 25*, 505–520.

Wu, H., Mark, D. S., Michael, J. H., Donald, A. W., & Fujiang, W. (2007). Appropriate application of the Standardized Precipitation Index in arid locations and dry seasons. *International Journal of Climatology, 27*, 65–79.

Yaduvanshi, A., Srivastava, P. K., & Pandey, A. (2015). Integrating TRMM and MODIS satellite with socioeconomic vulnerability for monitoring drought risk over a tropical region of India. *Physics and Chemistry of the Earth, Parts A/B/C, 83*, 14–27.

Yongjian, D., Daqing, Y., Baisheng, Ye., & Ninglian, W. (2007). Effects of bias correction on precipitation trend over China. *Journal of Geophysical Research, 112*, D13116. https://doi.org/10.1029/2006JD007938.

Zhiltsov, S. S., Zhiltsova, M. S., Medvedev, N. P., & Slizovskiy, D. Y. (2018). Water Resources of Central Asia. Historical Overview. In *Water Resources in Central Asia. International Context*, pp 9–24. Berlin/Heidelberg, Germany: Springer.

Springer Nature or its licensor (e.g. a society or other partner) holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.