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Assessment of meteorological drought using Standard Precipitation Index model (SPI) in Herat, Afghanistan

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Abstract

Assessing drought is a crucial component of effective drought risk management, stemming from diminished precipitation relative to the historical average, which subsequently impacts soil moisture and water reservoirs. The standard precipitation index (SPI) is commonly used to capture temporal and spatial variations. This research aims to evaluate the intensity, frequency, and duration of meteorological drought using SPI with time scales of 1, 3, 6, and 12 months in Herat Province, Afghanistan. The study encompasses 6 gauging stations with a 43-year record period in the region. The results show that with an increase in the time scale, the duration and frequency of drought increase. Additionally, the study reveals that the common extreme drought year for all stations was the year 2001, but the most extreme occurred in the year 2009 with an intensity two times greater than that of the year 2001. Due to the discrepancy of drought occurrence in each station, the findings suggest that for better drought management in the country, it is essential to analyze droughts in each local location. Over the past 43 years, the Cheldkhtaran station experienced the highest proportion of time in drought, accounting for 28.5%. Similarly, the Khosh Rabat station experienced droughts for 26.4%, the Nazdik-i-Herat station for 27.7%, the Pul-i-Hashemi station for 23.6%, and the Rabat-i-Akhund station for 26.9% of their respective time in the past 43 year.

Keywords: Meteorological Drought, Standardized Precipitation Index, Drought Management, Herat province, Pul-I-Hashemi

Introduction

Drought, a prolonged and severe lack of rainfall, has long been a formidable natural phenomenon that affects vast regions across the globe. With its relentless grip on water resources, agriculture, ecosystems, and communities, drought poses a significant threat to both the environment and human well-being. In recent years, the world has witnessed the intensified consequences of drought, highlighting the urgent need for proactive measures to mitigate its impact and foster environmental resilience. According to National Weather Service of USA, drought can be defined as a prolonged period of abnormally dry weather, causing a significant hydrologic imbalance in the affected area (National weather services, 2023). In simpler terms, it refers to an extended duration of exceptionally dry conditions that result in serious consequences, such as crop damage and water supply shortages (National weather services, 2023). The severity of a drought depends on the extent of moisture deficiency, the duration of the dry spell, and the geographical size of the impacted region (National weather services, 2023). Interestingly, there are four distinct ways to define drought: Meteorological Definition: This measures the deviation of precipitation from the normal average. However, since climatic conditions vary across locations, what may be considered a drought in one region might not be classified as such in another (National weather services, 2023). Agricultural Definition: This focuses on the inadequacy of soil moisture to meet the specific needs of a particular crop (National weather services, 2023). It indicates a situation where the available water in the soil can no longer sustain healthy crop growth. Hydrological Definition: This occurs when both surface and subsurface water sources fall below their usual levels. It encompasses the depletion of water in rivers, lakes, reservoirs, and groundwater (National weather services, 2023). Socioeconomic Definition: This refers to the point at which the physical scarcity of water begins to impact people's lives (National weather services, 2023). It highlights the consequences of water shortages on various socioeconomic aspects, including livelihoods, industries, and communities.

Afghanistan experienced unprecedented periods of prolonged dry weather starting in 1995, setting off a series of prolonged droughts that persisted until the winter season of 2002-2003, when substantial snowfall provided temporary respite (Wikipedia, 2023). However, this relief was short-lived as subsequent years witnessed a recurrence of drought conditions (Wikipedia, 2023). Notably, documented sources including the World Bank Working Paper by Ahmad and Wasig (Ahmad & Wasiq, 2004), the findings of Mayan (Miyan, 2015), and the comprehensive report by the Asia-Pacific Network for Global Change Research (APN, 2015), all concur on the occurrence of consecutive droughts from 1998 to 2001. In fact, the latter report explicitly designates the year 2001 as the most severe drought in recorded Afghan history. The convergence of prolonged droughts with ongoing conflict has exacerbated the plight of internally displaced populations, subjecting them to abject living conditions. Moreover, numerous communities have been compelled to seek meager livelihoods beyond their agricultural lands, amplifying their vulnerability. The repercussions of insufficient precipitation and snowfall between 2008 and 2010 have been particularly devastating, leading to substantial crop failures across six provinces: Herat, Jawzjan, Balkh, Badghis, Faryab, and Sar-e-Pul (ABC News, 2012). These circumstances have severely impacted the most marginalized segments of society, impeding their access to essential resources such as food and water, thereby compromising community health and nutrition (UPI, 2023). However, a glimmer of hope emerged in 2012 when Afghanistan finally witnessed the end of its protracted drought due to heavy snowfall (ABC News, 2012). This trend persisted until 2018, bringing some respite to water scarcity concerns (Wikipedia, 2023). Unfortunately, the year 2021 marked a resurgence of severe drought conditions, reaffirming the ongoing vulnerability of the nation to climatic fluctuations (Wikipedia, 2023).

The ability to accurately assess and monitor drought conditions is crucial for effective water resource management and mitigation strategies. In recent years, meteorological drought assessment models have gained significant attention as valuable tools in this endeavor. One such model is the Standardized Precipitation Index (SPI), which provides a comprehensive and standardized approach to quantifying meteorological drought. The assessment of meteorological drought using the SPI model has emerged as a popular and reliable method due to its simplicity, flexibility, and ability to capture both short-term and long-term drought events. The SPI characteristics make it possible for researchers to assign the intensity of drought or wet year phenomenon in a particular time scale for all points of the world having rain gauging stations. SPI merely uses monthly precipitation data. It is basically designated to specify the deficit of precipitations in various time scales. These time scales reflect the drought specific effects on the ability to access different water resources. The soil moisture conditions react toward precipitation short-term abnormalities, while groundwater, river flow and reservoir storage are affected by precipitation long term abnormalities. The SPI calculates the standardized departure of precipitation from the long-term average, providing a measure of the severity and duration of meteorological drought relative to historical norms. This approach allows for the comparison of drought conditions across different regions and time periods, enabling the identification of drought-prone areas and the monitoring of drought persistence.

Herat has been chosen as the study area for this research due to several key factors. Firstly, there is a noticeable gap in the literature regarding drought studies in Herat, presenting an opportunity to contribute new insights. Additionally, Herat experiences severe drought conditions, making it a pertinent location for investigating the impacts and implications of such events. Furthermore, Herat's geographical relevance extends to neighboring provinces such as Badghis and Farah, which share similar climatic conditions and vulnerability to drought. This allows our findings to have broader regional implications, enhancing their applicability to multiple areas facing similar challenges. The objective of this research is to assess meteorological drought using the SPI model and provide a comprehensive analysis of drought patterns, trends, and characteristics in a specific region. By examining historical meteorological data, we aim to identify periods of drought, quantify their severity. This research will contribute to a better understanding of drought dynamics and enhance our ability to anticipate and manage drought-related challenges. The findings of this study will have practical implications for water resource planning, agricultural management, and decision-making processes. By accurately characterizing meteorological drought events, stakeholders can develop proactive strategies to mitigate the impacts of drought, such as implementing efficient water conservation measures, adjusting irrigation practices, and ensuring the resilience of water supply systems.

Literature Review

A review of the literature shows that the most intense droughts almost happened in the last two decades in the country with the most intense drought in the year 2000, 2001, 2008, 2018 -2019, and 2021. And the moist year were from 1990 to 1998. According to a document published by world bank, in 2017-18 Afghanistan experienced a drought which affected 22 of its 34 provinces, exacerbating food insecurity, triggering internal displacement of people, and adversely affecting investments in the 2018-19 agricultural season (World Bank, 2023).

Changing climatic conditions, a growing population, and other environmental stressors will likely continue to have significant impact on food security going forward. By analyzing many document and publication, numbers state that the level of food insecurity and poverty in Afghanistan is directly related to the severity and duration of droughts happening in the country because the majority people of the country are engaged in agriculture. For example, in 2018, over 170,000 people were displaced in Afghanistan's western region alone after drought conditions adversely affected livelihoods, forcing locals into chronic food insecurity (OCHA, 2019). In mid-April 2018, the Afghan government declared a drought. In mid-May 2018, the Humanitarian Country Team revised the 2018 Humanitarian Response Plan to facilitate fundraising (OCHA, 2019).

In some similar studies; for example, in Helmand and Kabul river basin similar results were found. In the pursuit of unlocking the secrets hidden within the enigmatic Helmand River Basin (HRB) in Afghanistan, Mohammad Musa Alam embarked on a scientific odyssey that has forever altered our understanding of drought dynamics in this crucial region (Alami & Tayfur, 2022). With unparalleled dedication and rigor, Alam and his team meticulously assessed four critical stations—Lashkargah, Farah, Adraskan, and Gardandiwal—to evaluate the ever-present specter of drought. Armed with an impressive 37-year repository of monthly recorded precipitation data spanning from 1979 to 2015, the researchers embarked on an ambitious mission to uncover the most fitting drought indices for this vital basin. Their scholarly expedition unveiled a treasure trove of insights, utilizing various drought index (DI) methods—each with its own unique approach—to shed light on the complexities of drought occurrence. The Standardized Precipitation Index (Normal-SPI, Log-SPI, and Gamma-SPI), the Percent of Normal (PN), and the Deciles were the tools of choice, enabling them to decode the mysteries concealed within the annual long-term precipitation data. Among these indices, the log-SPI and the gamma-SPI emerged as formidable prognosticators, revealing with remarkable accuracy the specter of extreme drought conditions lurking in the shadows. In stark contrast, the normal-SPI offered glimmers of hope, providing insights into periods of wetness and lesser dry spells, offering a ray of respite amid arid adversity (Alami & Tayfur, 2022). The research findings reverberate with a profound revelation—highlighting the PN and the Deciles methods as potent predictors, surpassing the SPI methods in identifying drought years. Notably, the Deciles method outshined its peers, illuminating prolonged stretches of extreme and severe drought, accentuating the urgency of addressing this critical environmental concern (Alami & Tayfur, 2022). As they navigated the labyrinth of historical data, the researchers unearthed a trail of evidence, unveiling various drought intensities that marked the years 1985, 1987, 1994, 1997, 1999, 2000, 2001, 2002, 2003, and 2004 across all stations (Alami & Tayfur, 2022). They found the year 2000 as the extreme drought year for Gardandiwal station and 1994 for Adraskan station. Years 1997 and 2000 are predicted as the severe drought years for Lashkargah station and 1987 for Farah station. The common moderate drought conditions are observed as 1985 and 2002 (Alami & Tayfur, 2022).

In addition, another study by Mohammad Musa Alami on the Kabul River Basin (KRB) provides crucial insights into the meteorological drought patterns in this socio-economically significant region of Afghanistan. By utilizing a comprehensive dataset spanning 38 years of monthly precipitation records, the study examined four key stations—Asma, Gulbahar, Pul-I-Surkh, and Pul-I-Kama—and applied various drought indices to assess the correlation among them, aiming to identify the most suitable method for drought monitoring in the KRB. The study employed several drought indices, including the Standardized Precipitation Index (SPI), Percent of Normal Precipitation Index (PNPI), Deciles Index (DI), and China-Z Index (CZI). These indices enabled a multifaceted analysis, providing a comprehensive understanding of drought conditions within the basin. The research findings revealed a continuous spell of drought conditions in the Kabul River Basin from 2000 to 2004, with an alarming peak of extreme drought observed in 2001 (Alami & Hayat, and Tayfur, 2017). This peak corresponds to the reported occurrence of the worst drought experienced in the region, highlighting the accuracy of the research's drought detection methodologies. Further examination of the drought severity at specific stations revealed distinct patterns. The Asmar Station experienced the most extreme drought in the years 2000, 2001, 2002, and 2004, with the peak severity recorded in 2000 (Alami & Hayat, and Tayfur, 2017). Gulbahar and Pul-I-Surkh Stations encountered their peak extreme drought years in 2001, encompassing the years 2000, 2001, and 2002 (Alami & Hayat, and Tayfur, 2017). Meanwhile, the Pul-I-Kama Station witnessed its most severe drought conditions in 2001, spanning the years 2000 and 2001 (Alami & Hayat, and Tayfur, 2017). Additionally, the study identified moderate droughts in 2010 and 1993 for Pul-I-Kama Station. These findings underscore the significance of the research's contributions to understanding drought dynamics in the Kabul River Basin. The identification of specific extreme and moderate drought years at different stations highlights the localized nature of drought events, stressing the importance of station-specific analyses to comprehend the diverse impacts of drought across the region.

In one of the other studies conducted by Kazim Nosrati in West Azarbaijan Province, Iran, offers valuable insights into the characteristics of meteorological drought using the Standardized Precipitation Index (SPI) with different time scales. Although not directly conducted in Afghanistan, the proximity and shared meteorological characteristics between Iran and Afghanistan make this study highly relevant for your literature review on drought assessment in Herat, Afghanistan. The primary objective of the research was to assess key drought characteristics, including intensity, frequency, and duration, by employing the SPI with time scales of 1, 3, 6, 12, and 24 months. The study encompassed a substantial dataset from 38 gauging stations, spanning a record period of 32 years in West Azarbaijan Province, Iran. To evaluate the recent drought during 1998-2001, the researchers computed the SPI indices for the specified time scales and examined the variations in drought behavior over different return periods. The findings of the research illuminate critical aspects of drought behavior in the study area. As the return period and time scale increased, the duration of drought events exhibited a corresponding increase (Nosratif & Zareiee, 2011). This observation implies that as drought conditions persist for longer durations, the severity and impacts of drought may intensify, posing significant challenges for water resources and socio-economic activities. Furthermore, the study revealed a linear decrease in the frequency of drought events with an increase in time scale. This suggests that longer time scales capture more prolonged drought events, leading to a reduction in the frequency of drought occurrence. However, it is crucial to note that despite the reduced frequency, the duration of drought events still demonstrated an increase.

Research Method

This study adopts a quantitative research design to assess meteorological drought using the Standardized Precipitation Index (SPI) model. Although there are many models being used to assess droughts like Palmer Drought Severity Index (PDSI), which is a widely used drought index that takes into account precipitation, temperature, and soil moisture conditions. Standardized Precipitation-Evapotranspiration Index (SPEI), which is an extension of the SPI model that incorporates both precipitation and potential evapotranspiration. Reconnaissance Drought Index (RDI), which combines precipitation and temperature data to evaluate drought conditions. It considers the sensitivity of different regions to drought and accounts for temperature impacts on drought severity. But in this study, we used SPI model approach because it is really easy to use, analyze the output data, and is recommended by the World Meteorological Drought Organization.

The Standardized Precipitation Index (SPI) is a widely used drought index that provides a standardized measure of precipitation anomalies over a specific time scale (Edward & Mackee, 1997). It allows for the assessment and comparison of meteorological drought severity across different regions and time periods. The SPI was developed to quantify and monitor drought conditions based solely on precipitation data. The index represents the number of standard deviations by which the observed precipitation deviates from the long-term mean for a specific time scale. SPI was developed in Colorado by McKee et al (1993), and is based on the probability distribution of precipitation and requires less input data and calculation efforts than PDSI, and is reported to be able to identify emerging droughts sooner than Palmer Index (Guttman, 1998).

The recording data of monthly precipitation of 6 stations, in Herat province based on long-term recording data, which is 44 years (1979-2023) have been selected. The SPI calculation in different time steps (1-month, 3-month, 6-month, and 12-month) for any location is based on the long-term precipitation record for a desired period. This long-term record is fitted to a probability distribution, which is then transformed into a normal distribution so that the mean SPI for the location and desired period is zero (Edward & Mackee, 1997). Table 0 shows the classes of SPI. Positive SPI values indicate greater than median precipitation and negative values indicate less than median precipitation. Similar to the PDSI, SPI may be used for monitoring both dry and wet conditions. A drought event starts when SPI value reaches -1.0 and ends when SPI becomes positive again. The positive sum of the SPI for all the months within a drought event is referred to as "drought magnitude". After calculating the intensity of drought, the duration of drought in each scale was elicited. After careful investigation and analyzing data using excel, we have elicited the most severe drought ever happened, total duration of drought in each time scale from year 1979 to 2023, and the frequency of the extreme drought (SPI value -2 and below are classified as extreme drought), and then we analyzed these data.

The SPI calculation involves several steps. First, the long-term precipitation data are collected and used to calculate the mean and standard deviation for the desired time scale. The time scale can range from short-term (1-month) to long-term (12-month), capturing different aspects of drought conditions. Next, the observed precipitation data for a specific location and time period are transformed into standardized values using the mean and standard deviation calculated from the long-term data. The resulting standardized values represent the SPI for the corresponding time scale.

Categorization of SPI values into classes	
Class	**SPI**
Extremely wet	**2+**
Very wet	**1.5 to 1.99**
Moderately wet	**1.0 to 1.49**
Normal	**-.99 to .99**
Moderately dry	**-1.0 to -1.49**
severely dry	**-1.5 to -1.99**
Extremely dry	**-2 and less**

Table 0: Categorization of SPI values into classes

A 1-month SPI map is very similar to a map displaying the percentage of normal precipitation for a 30-day period (SPI User Guide). In fact, the derived SPI is a more accurate representation of monthly precipitation because the distribution has been normalized. For example, a 1-month SPI at the end of November compares the 1-month precipitation total for November in that particular year with the November precipitation totals of all the years on record (SPI User Guide). Because the 1-month SPI reflects short-term conditions, its application can be related closely to meteorological types of drought along with short-term soil moisture and crop stress, especially during the growing season. The 3-month SPI provides a comparison of the precipitation over a specific 3-month period with the precipitation totals from the same 3-month period for all the years included in the historical record (SPI User Guide). In other words, a 3-month SPI at the end of February compares the December–January– February precipitation total in that particular year with the December–February precipitation totals of all the years on record for that location. Each year data is added, another year is added to the period of record, thus the values from all years are used again. The values can and will change as the current year is compared historically and statistically to all prior years in the record of observation. A 3-month SPI reflects short- and medium-term moisture conditions and provides a seasonal estimation of precipitation (SPI User Guide). According to Yuanda Zhang's research, the 3-month and 6-month SPI values indicate seasonal drought, while the 9-month SPI value represents intermediate drought (Zhang and others, 2023). The 6-month SPI compares the precipitation for that period with the same 6-month period over the historical record (SPI User Guide). For example, a 6-month SPI at the end of September compares the precipitation total for the April–September period with all the past totals for that same period. The 6-month SPI indicates seasonal to medium-term trends in precipitation. The 9-month SPI provides an indication of inter-seasonal precipitation patterns over a medium timescale duration (SPI User Guide). Droughts usually take a season or more to develop. SPI values below -1.5 for these timescales are usually a good indication that dryness is having a significant impact on agriculture and may be affecting other sectors as well. This time period begins to bridge a short-term seasonal drought to those longer-term droughts that may become hydrological, or multi-year, in nature.

Data analysis using the SPI typically involves examining the temporal patterns and trends of the index over time. SPI values are often graphed or mapped to visualize drought conditions and their changes over various time scales. Additionally, SPI values can be compared between different locations or regions to assess spatial variations in drought severity. The basis of SPI approach is the calculating probabilities of precipitation for each time scale. In a general point of view, for analyzing the precipitation data in monthly scale during a record period (preferably 30 years or more), it is required to form total precipitation time series in an ideal scale. The main problem in this case is fitting an appropriate statistical distribution on a particular time series. Tom (1996) realized that gamma distribution fits well for some climatological data such as precipitation time series (Edward & Mackee, 1997). To obtain experimental accumulation probabilities, first precipitation data will be arranged as ascendant then the value of experimental probabilities. For an easy access to Z or SPI values, it is better to use Abramowitz and Stegun approximate, this approximation transforms the accumulation possibilities to standard normal random variant (Edward & Mackee, 1997). Actually SPI is a standard variant that shows diversion values upper or lower than average. Different applications of SPI including: Frist, Drawing SPI series (in each time scale) in a chart is a good index of drought phenomenon in a particular place. Second, SPI can be used for spatial analysis of drought, so makes it possible to compare different stations in various climatic regions ignoring differences between their normal precipitations. Third, SPI can be calculated for short time scales (for example, one month). Forth, by studying drought, it is possible to analyze frequency and duration of different values of SPI.

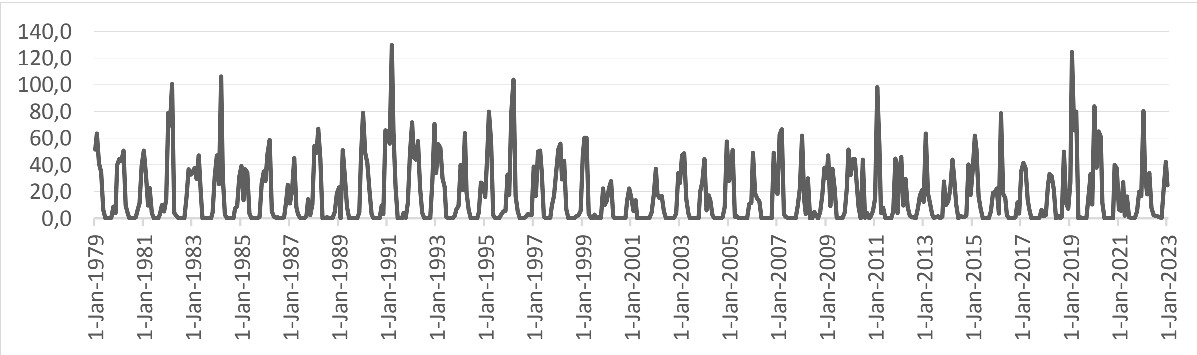

Figure 1 Precipitation History for Cheldkhtaran Station (mm)

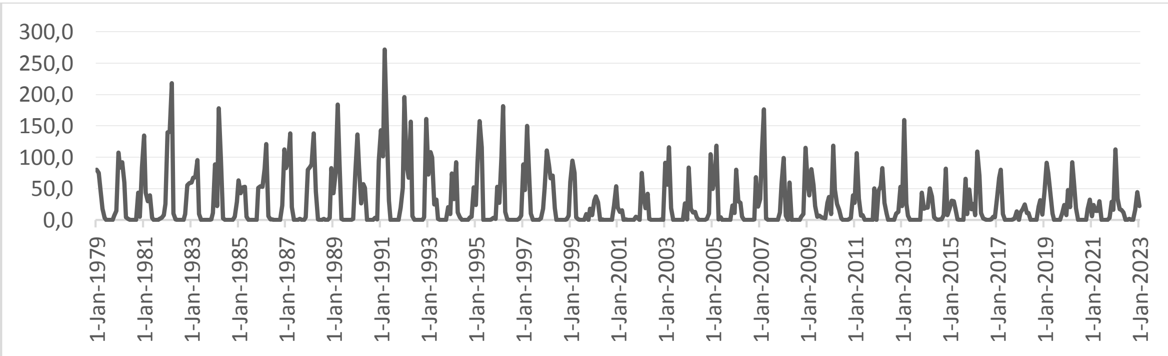

Figure 2 Precipitation History for Khosh Rabat Station (mm)

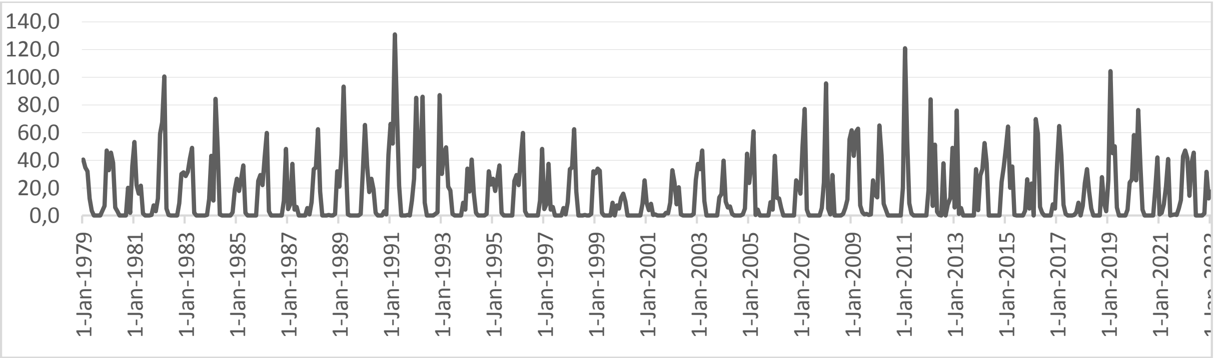

Figure 3 Precipitation History for Nazdik-i-Herat Station (mm)

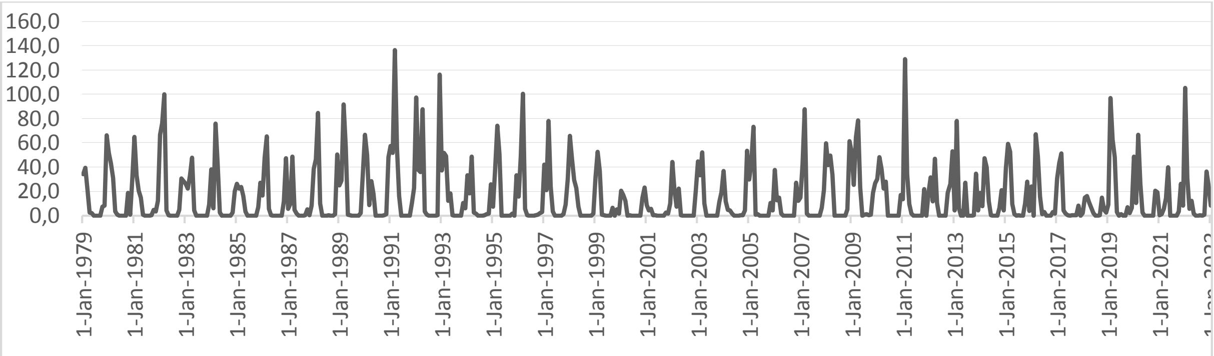

Figure 4 Precipitaion History for Pul-i-Hashemi Station (mm)

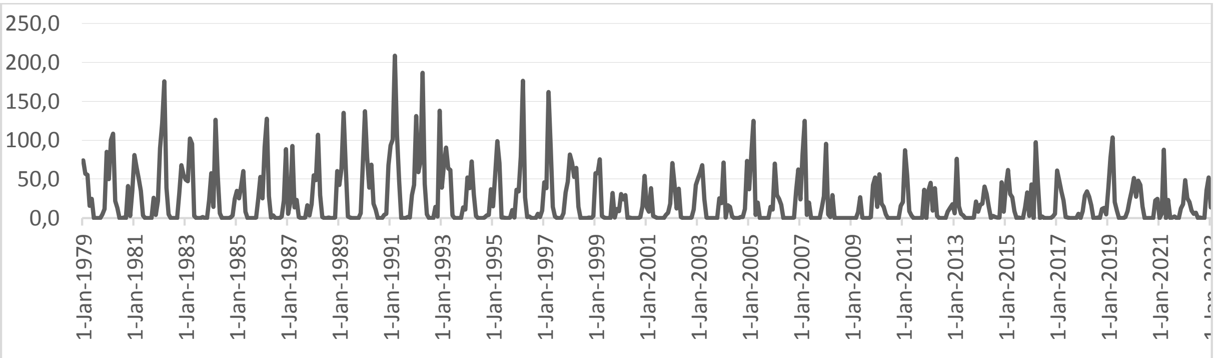

Figure 5 Precipitation History for Rabat-i-Akhund Station (mm)

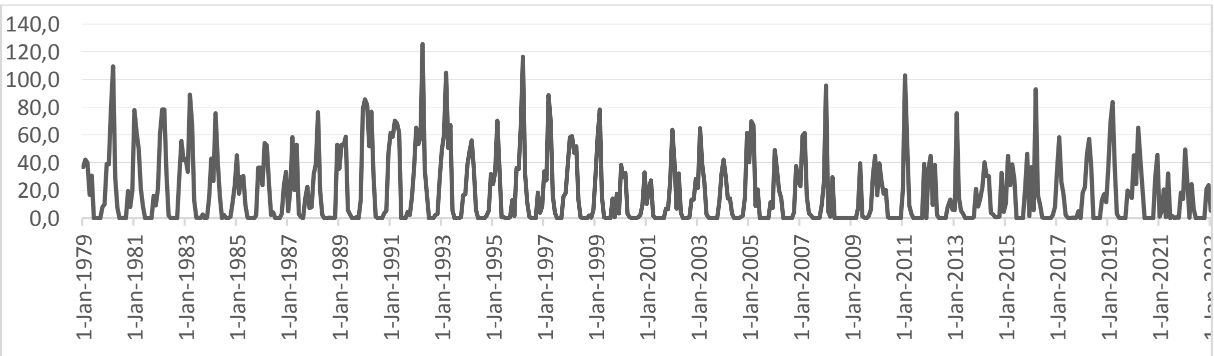

Figure 6 Precipitation History for Tagab Ghaza Staion (mm)

Results

Table 1 presents the most extreme SPI values recorded at various stations and time scales spanning from 1979 to 2023. Among the stations assessed, the most severe drought event occurred at Tagab Ghaza station in the year 2009, with an exceptionally low SPI value of -5.58. This extreme negative SPI value indicates the severity of the drought that occurred during that specific year.

	Extreme observed value of SPI (Dry condition)									
Station	**SPI 1**	**Year**	**SPI 3**	**Year**	**SPI 6**	**Year**	**SPI 9**	**Year**	**SPI 12**	**Year**
Cheldkhtaran	-3.46	2001-04-01	-3.44	2018-01-01	-3.54	2018-01-01	-3.34	2018-01-01	-2.97	2001-12-01
Khosh Rabat	-2.29	2008-02-01	-3.35	2002-12-01	-3.35	2002-12-01	-2.83	2001-12-01	-3.11	2001-12-01
Nazdik-i-Herat	-3.06	2021-01-01	-3.25	2021-03-01	-2.9	2001-06-01	-2.9	2001-09-01	-3.05	2001-12-01
Pul-i-Hashemi	-3.04	2021-01-01	-3.51	2021-03-01	-3.2	2001-06-01	-3.2	2001-09-01	-3.23	2001-12-01
Rabat-i-Akhund	-2.7	2021-04-01	-3.1	2009-04-01	-4.01	2009-04-01	-5.11	2009-02-01	-4.08	2009-04-01
Tagab Ghaza	-2.71	2021-04-01	-3.48	2009-04-01	-4.59	2009-04-01	-5.58	2009-02-01	-4.59	2009-04-01

Table 1: The characteristics of the most extreme droughts using SPI time-scales

	SPI 1	**SPI 3**	**SPI 6**	**SPI 9**	**SPI 12**
Station					
Cheldkhtaran	7	15	20	16	15
Khosh Rabat	5	11	14	16	11
Nazdik-i-Herat	5	13	21	26	22
Pul-i-Hashemi	4	13	19	27	28
Rabat-i-Akhund	4	9	17	14	12
Tagab Ghaza	9	10	15	14	13

Table 2: Frequency of the most severe droughts (Below -2 SPI value) from 1979 to 2023

	SPI 1(Year)	**SPI 3(Year)**	**SPI 6(Year)**	**SPI 9(Year)**	**SPI 12(Year)**
Station					
Cheldkhtaran	6.75	11.16	13.33	12.25	12.58
Khosh Rabat	6.08	8.58	12	11.33	11.5
Nazdik-i-Herat	5.91	9.58	13	11.91	10.25
Pul-i-Hashemi	5.83	6.75	10.33	10.16	8.5
Rabat-i-Akhund	5.83	10.16	12.75	11.58	12.66
Tagab Ghaza	5.83	9.91	10.91	8.5	9.25

Table 3: Total duration of droughts for each station from 1979 to 2023 (from moderate drought to sever drought)

Cheldkhtaran

The results of the SPI analysis for the Cheldkhtaran station are visually represented in the graph below. It is evident from the graph that the SPI values calculated using a 3-month time scale exhibit greater diversity and intensity compared to those obtained with a 9-month time scale for all stations analyzed. It shows that Chedkhtaran station experienced extreme seasonal droughts (3-month and 6-month SPI value) in the year 1996-1997, 1998-1999, 2000-2003, 2010-2011, 2017-2018, 2021. And extreme long term drought (9-month and 12-month) in the year 1989, 1999-2004, 2017-2019. Table 1 provides specific extreme SPI values observed for all station at various time scales: The most extremes value for the 9-month SPI is -3.54, which occurred at the beginning of the year 2018. The most extremes value for the 1-month SPI is -3.46, recorded in the year 2001. The most extremes value for the 3-month SPI is -3.44, noted in the year 2018. The most extremes value for the 6-month SPI is -3.54, also observed in the year 2018. The most extremes value for the 12-month SPI is -2.97, observed in the year 2001.

Table 2 indicate the frequency of most severe drought (with SPI value below -2). It shows that Cheldkhtaran station has experienced 7 times extreme drought from 1979 to 2023 with 1-month SPI and 20 times with 6-month SPI. This indicated that as the time scale increase the frequency of drought increase. Also, Table 3 indicate the overall duration of drought (moderate drought to extreme drought) that Cheldkhtaran station experienced from year 1979 to 2023. It shows that Cheldkhtaran station has experienced 6.75 years of drought with 1-month SPI and 13.33 years of drought with 6-month SPI, which imply that as the time scale increase the duration of drought increase.

Overall, these findings suggest that the Cheldkhtaran station has encountered several severe drought events during the study period, with notable variations in intensity and duration depending on the time scale considered for SPI calculation.

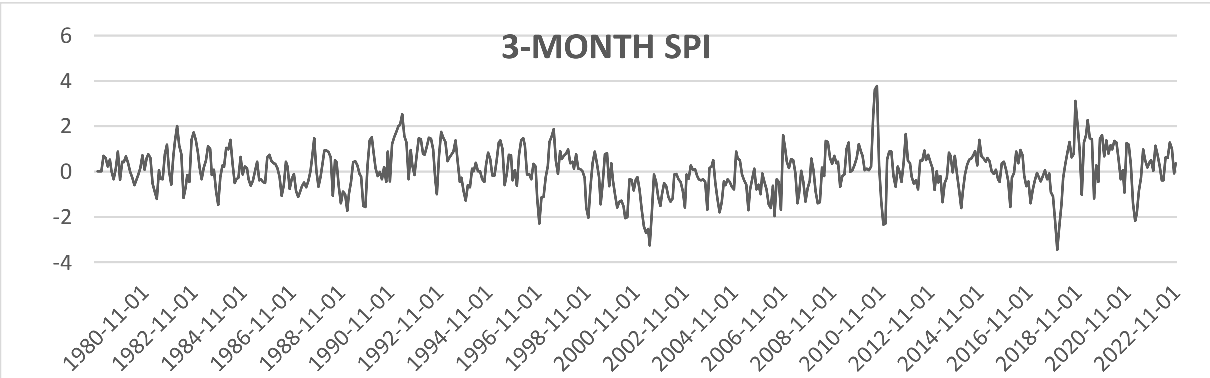

Figure 7: 3- Month SPI for Cheldkhtaran station

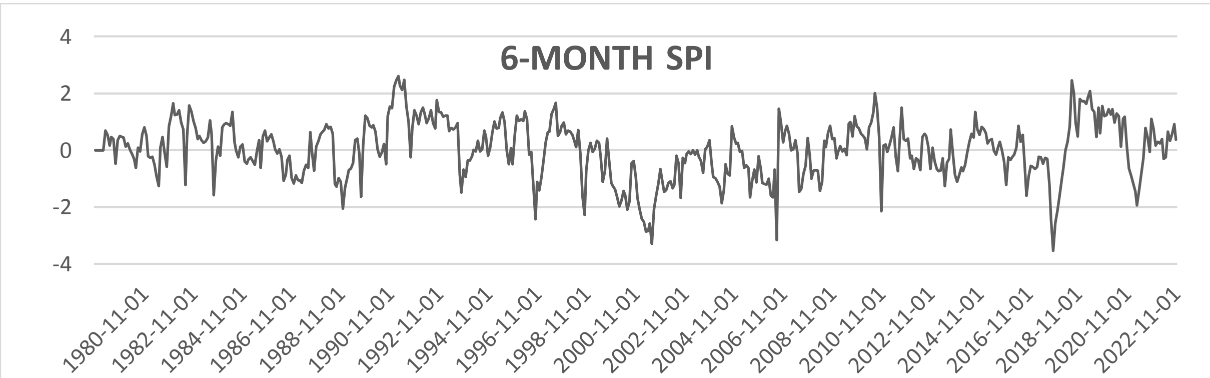

Figure 8: 6-Month SPI for Cheldkhtaran Station

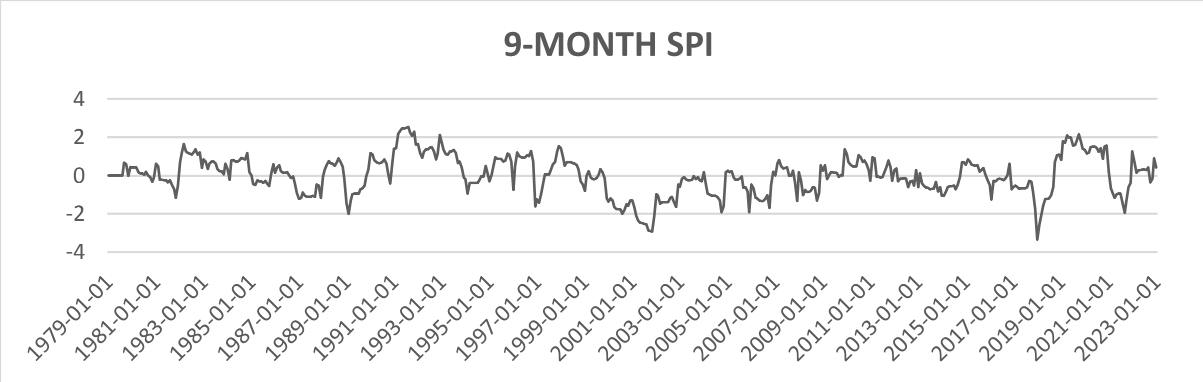

Figure 9: 9- Month SPI for Chedkhtaran station

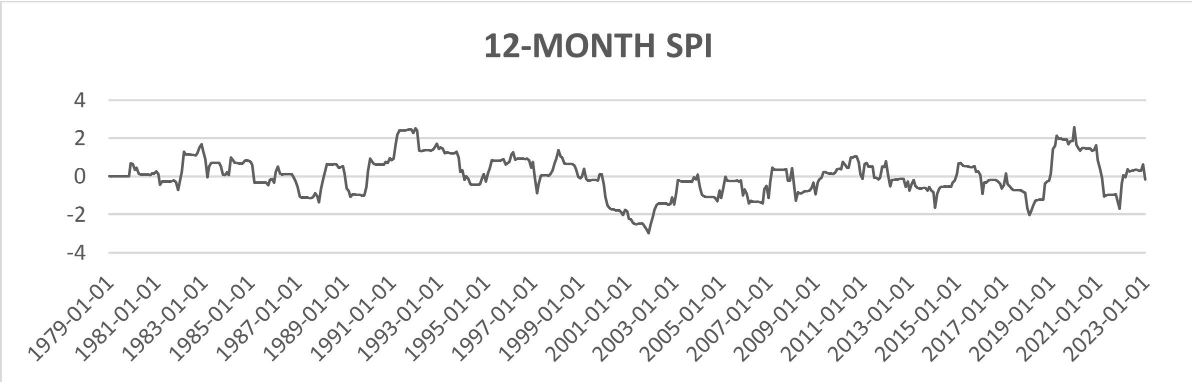

Figure 10: 12-Month SPI for Cheldkhtaran Station

Khash Rabat

The SPI analysis results for the Khash Rabat station are visually depicted in the graph below. The graph illustrates the SPI values calculated for different time scales, providing valuable insights into the station's meteorological drought patterns. According the SPI graph, Khash Rabat station experienced extreme seasonal droughts (3-month and 6-month SPI value) in the year 1998-1999, 2000-2003, 2016-2018, 2021. And extreme long term drought (9-month and 12-month) in the year 1996-1997, 1999-2005, 2017-2019.

Table 1 presents the extreme SPI values observed for the Khash Rabat station at various time scales: The most extremes value for the 9-month SPI is -3.35, which occurred in the year 2002. This indicates a severe and prolonged drought event during that period, affecting the region for a considerable duration. The most extremes value for the 1-month SPI is -2.29, recorded in the year 2008. Although relatively less severe compared to the longer-term events, this indicates a shorter-term drought episode that might have had localized impacts on the station. The most extremes value for the 6-month SPI is -2.83, noted in the year 2001. This signifies a significant and sustained drought occurrence, likely impacting agriculture, water resources, and local communities during that period. The most extremes value for the 12-month SPI is -3.11, also observed in the year 2001. This further emphasizes the severity of the drought in 2001, extending its impact over a year.

According to Table 2 Khash Rabat station has experienced 5 times extreme drought from 1979 to 2023 with 1-month SPI and 14 times with 6-month SPI. The same is also true for all station that as the time scale increase the frequency of drought increase. Also, Table 3 shows that Khash Rabat station experienced 6.08 years of drought for 1-month SPI and 12 years for

6-month SPI from year 1979 to 2023, which again imply that as the time scale increase the duration of drought increase. The SPI analysis demonstrates that the Khash Rabat station has experienced multiple extreme drought events during the study period. The severity and duration of these drought events vary based on the chosen time scale for SPI calculation.

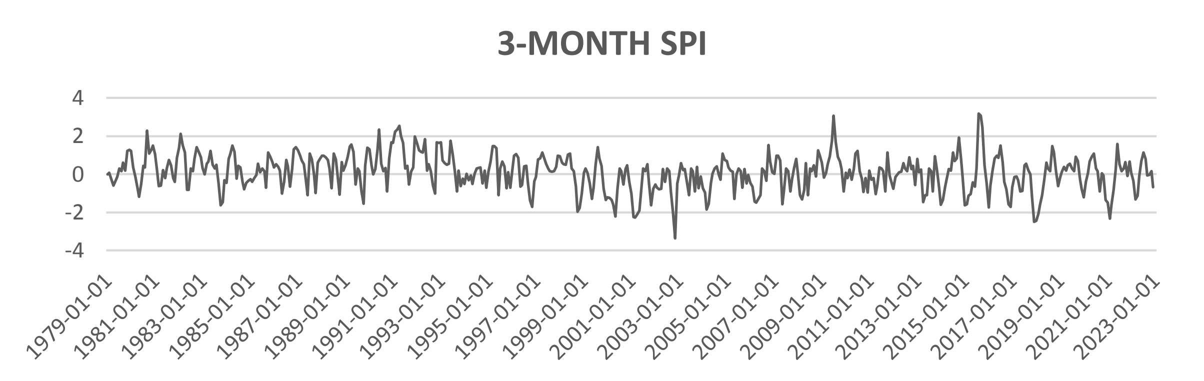

Figure 11: 9- Month SPI for Khash Rabat station

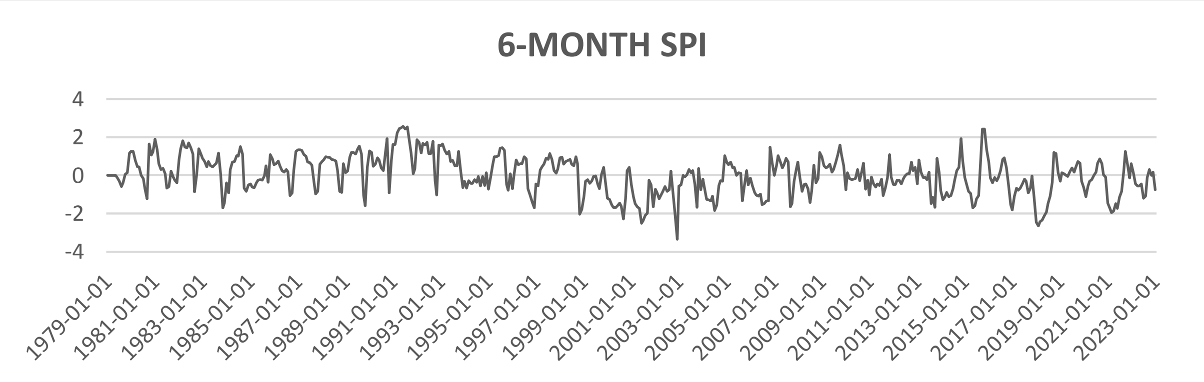

Figure 12: 6-Month SPI for Khash Rabat Station

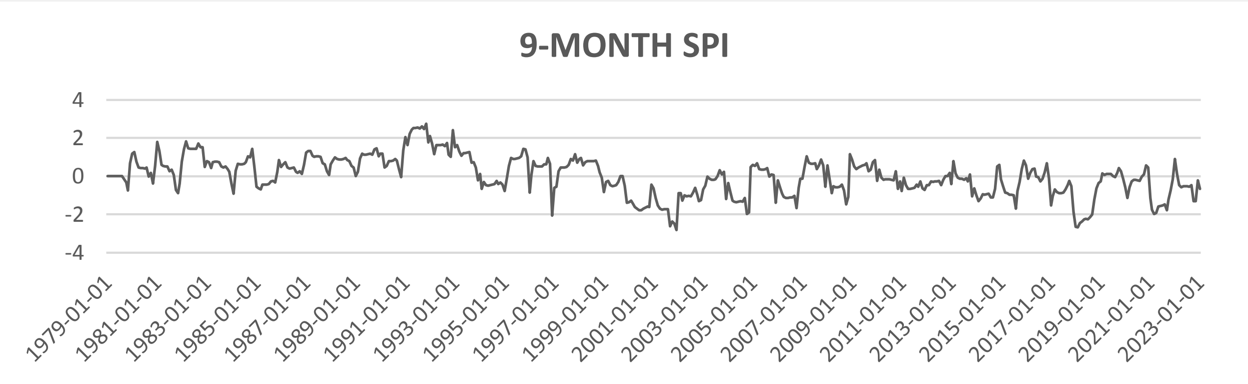

Figure 13: : 9- Month SPI for Khash Rabat station

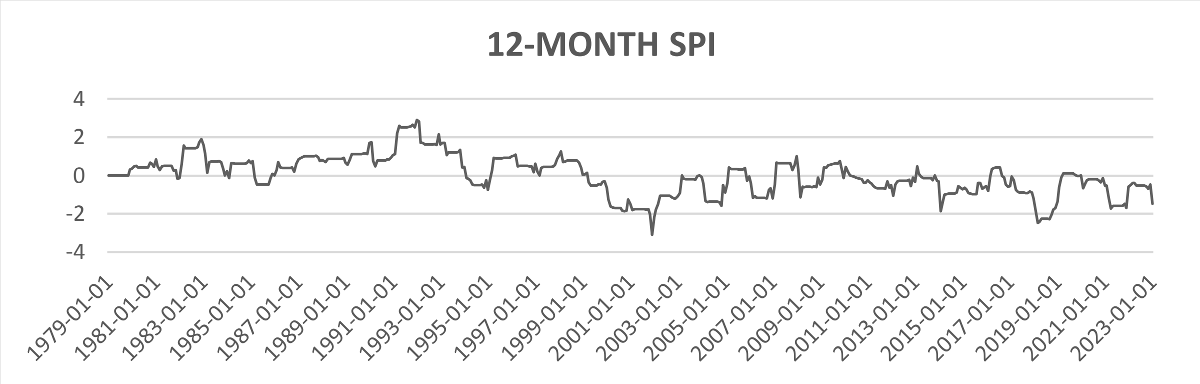

Figure 14: 12-Month SPI for Khash Rabat Station

Nazdik-I-Herat

According to SPI graph for Nazdik-i-Herat station, it shows that the station experienced extreme seasonal droughts (3-month and 6-month SPI value) in the year 1999-2004, 2010, 2011, 2013, 2016-2018, and 2021. And extreme long term drought (9-month and 12-month) in the year 1999-2005, 2010, 2011, 2012, and 2017-2018. On the other hand, the most extremes value for the 1-month SPI is -3.06, recorded in the year 2021. This indicates a severe short-term drought event that likely had rapid and localized impacts on the station's surroundings during that specific time period. The most extremes value for the 3-month SPI is -3.25, also noted in the year 2021. This highlights a prolonged and intense drought period lasting for three months, potentially affecting agriculture, water resources, and communities in the area. The most extremes value for the 6-month SPI is -2.9, observed in the year 2001. This indicates a significant drought episode with a moderate duration, impacting the station and its vicinity for half a year. The most extremes value for the 9-month SPI is -2.9, also recorded in the year 2001. This aligns with the findings for the 6-month SPI, further emphasizing the severity of the drought conditions that persisted for nine months during that year. The most extremes value for the 12-month SPI is -3.05, noted in the year 2001. This signifies a year-long drought event, affecting the region for an extended period and likely having substantial implications on various sectors. According to table 2 and 3, Nazdik-I-Herat station has experienced 5 times of severe drought with 1-month and 21 times of severe drought with 6-month SPI form year 1979 to 2023. Also, the station has experienced 5.91 years of drought with 1-month SPI and 13 years with 6-month SPI from 1979 to 2023.

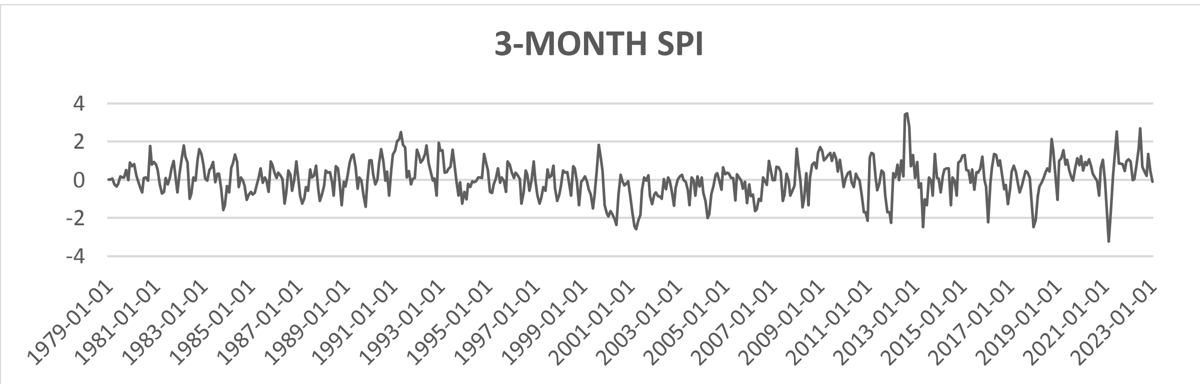

Figure 15: 9- Month SPI for Nazdik-I-Herat station

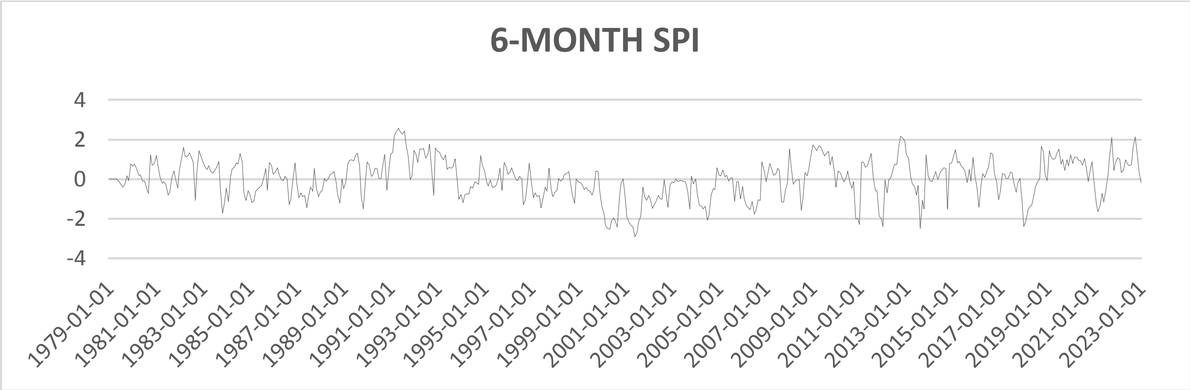

Figure 16: 6-Month SPI for Nazdik-i-Herat Station

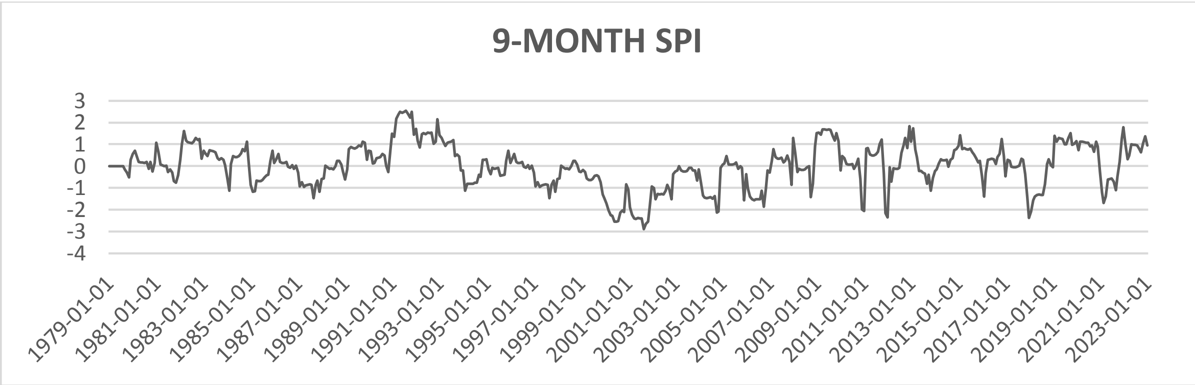

Figure 17: 9- Month SPI for Nazdik-I-Herat station

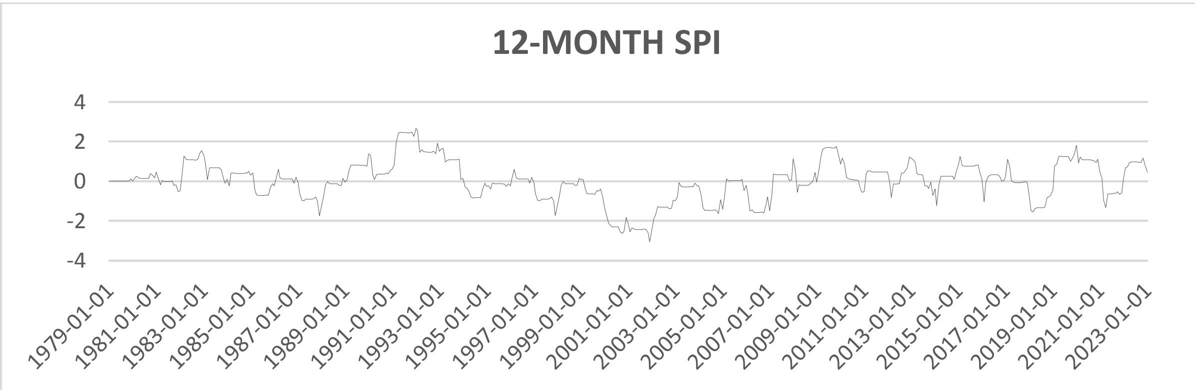

Figure 18: 12-Month SPI for Nazdik-i-Herat Station

Pul-I-Hashemi

Pul-i-Hashemi station experienced extreme seasonal droughts (3-month and 6-month SPI value) in the year 1998-2000, 2001-2002, 2004, 2008, and 2017-2021. And extreme long term drought (9-month and 12-month) in the year 1999-2003, 2004, 2017-2019, and 2021. However, the most extremes value for the 3-month SPI is -3.52, recorded in the year 2021. This signifies a severe and concentrated drought event lasting for three months, likely exerting significant pressure on the station's environment and water resources during that specific period. The most extremes value for the 1-month SPI is -3.04, also noted in the year 2021. This indicates a short-term, intense drought episode that might have rapidly impacted the station and its vicinity, affecting agricultural activities and local communities. The most extremes value for the 6-month SPI is -3.2, observed in the year 2001. This highlights a prolonged drought period lasting half a year, likely leading to water scarcity and ecological challenges in the area. The most extremes value for the 9-month SPI is -3.2, also recorded in the year 2001. This aligns with the findings for the 6-month SPI, suggesting that the station experienced an extended drought event for nine months during that particular year. The most extremes value for the 12-month SPI is -3.23, noted in the year 2001. This indicates a year-long drought event, potentially impacting various sectors such as agriculture, water supply, and socio-economic activities. Table 2 shows that Pul-I-Hashemi station has experienced 4 times severe drought with 1-month SPI and 19 times with 6-month SPI from 1979 to 2023. Table 3 also shows 5.83 years of drought for 1-month and 10.33 years for 6-month SPI for the past 43 years.

The SPI analysis reveals that the Pul-I-Hashemi station has encountered several extreme drought events during the study period. The severity and duration of these events varied depending on the selected time scales for SPI calculation. Understanding drought patterns at different time scales is crucial for developing effective strategies to mitigate the impacts of drought in the Pul-I-Hashemi region. These findings can assist in devising appropriate drought preparedness plans, resource management, and sustainable development initiatives to address the challenges posed by drought in the area.

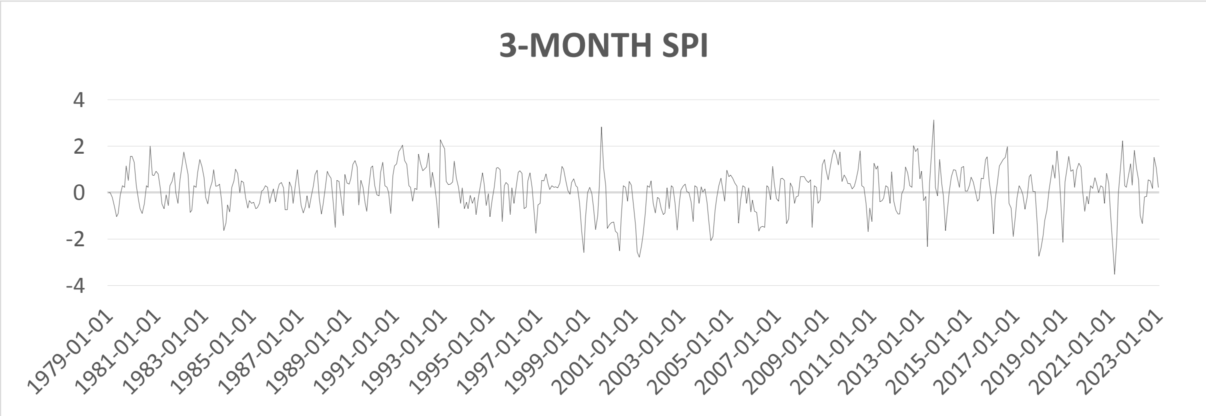

Figure 19: 3- Month SPI for Pul-I-Hashemi station

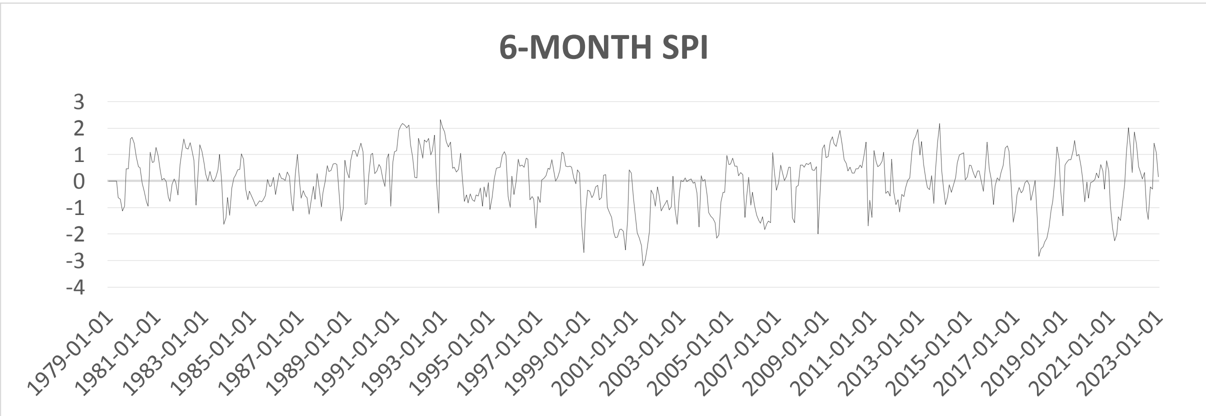

Figure 20: 6-Month SPI for Pul-i-Hashemi Station

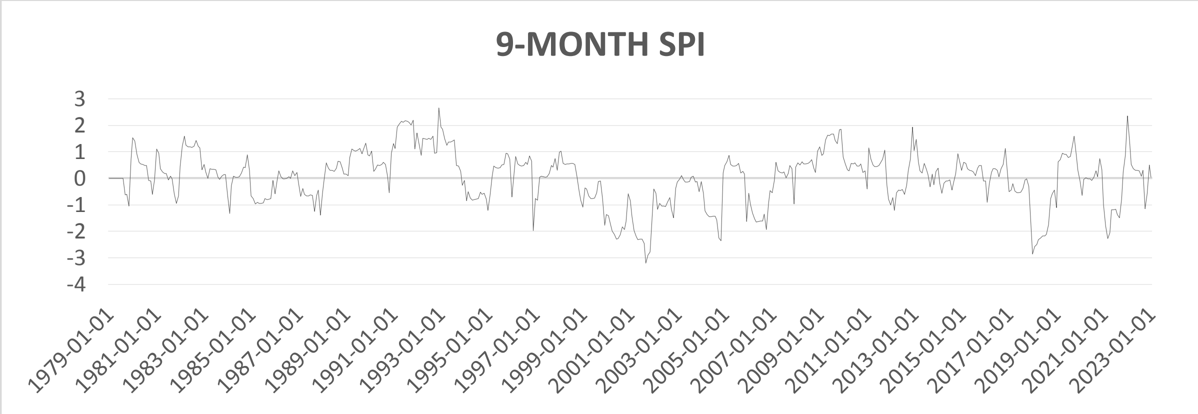

Figure 21: 9- Month SPI for Pul-I-Hashemi station

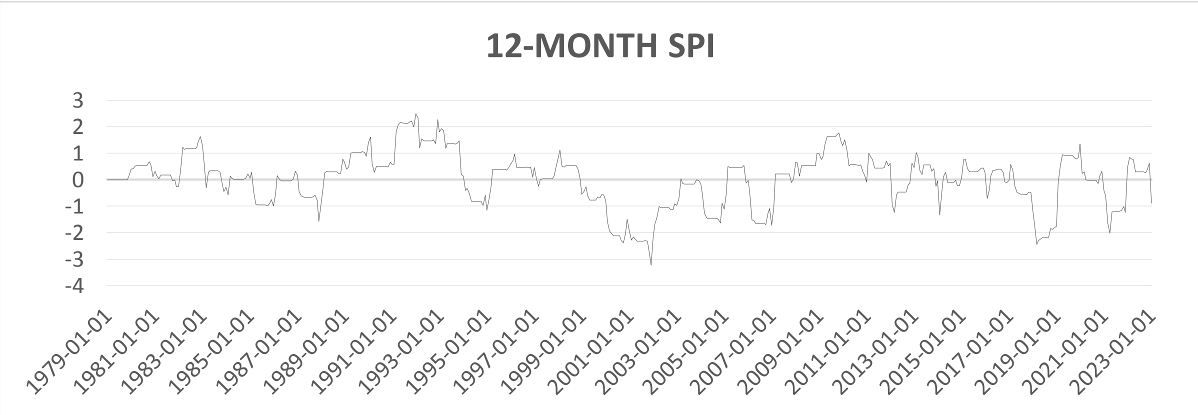

Figure 22: 12-Month SPI for Pul-i-Hashemi Station

Rabat-I-Akhand

As the result shows, Rabat-I-Akhand station has experienced the most severe droughts ever happened in Afghanistan after Tagab Ghaza station. Results show the most extremes value for the 9-month SPI is -5.11, recorded in the year 2009. This exceptionally low SPI value indicates an extremely severe and prolonged drought event, lasting for nine months. Such a severe drought likely had significant impacts on agriculture, water resources, and the livelihoods of communities relying on the station's surroundings. The most extremes value for the 1-month SPI is -2.7, observed in the year 2021. This indicates a short-term drought episode, albeit with less severity compared to the long-term drought events. While the 1-month SPI value suggests localized water stress, it may not have had a severe and widespread impact on the station's region. The most extremes value for the 6-month SPI is -4.01, noted in the year 2009. This highlights a prolonged drought event lasting six months, which could have resulted in agricultural losses, reduced water availability, and ecological challenges in the area. The most extremes value for the 12-month SPI is -4.08, also recorded in the year 2009. This aligns with the findings for the 6-month SPI, indicating a year-long drought period, potentially leading to water scarcity and ecological stress in the station's vicinity. The data in the Table 2 and 3 show that the Rabat-I-Akhand station has experienced 4 and 17 years of drought from year 1979 to 2023 for 1-month and 6-month SPI respectively.

The SPI analysis reveals that the Rabat-I-Akhand station has experienced various extreme drought events during the study period. The most severe drought occurred in 2009, affecting the station for extended periods at both the 9-month and 12-month time scales. Understanding the severity and duration of these drought events is crucial for implementing effective drought preparedness and mitigation measures in the Rabat-I-Akhand region. Such actions can help minimize the impact of drought on local communities and ecosystems, ensuring the sustainable management of water resources and enhancing the region's resilience to future drought occurrences.

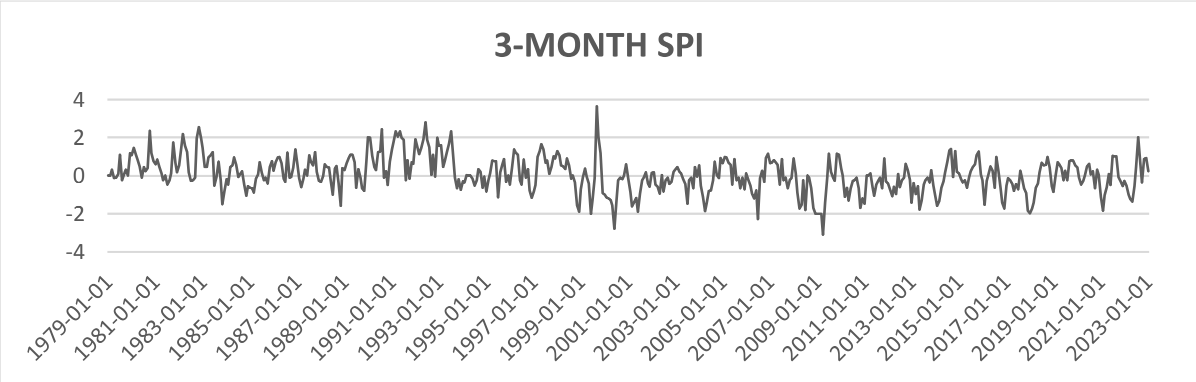

Figure 23: 3- Month SPI for Rabat-I Akhand station

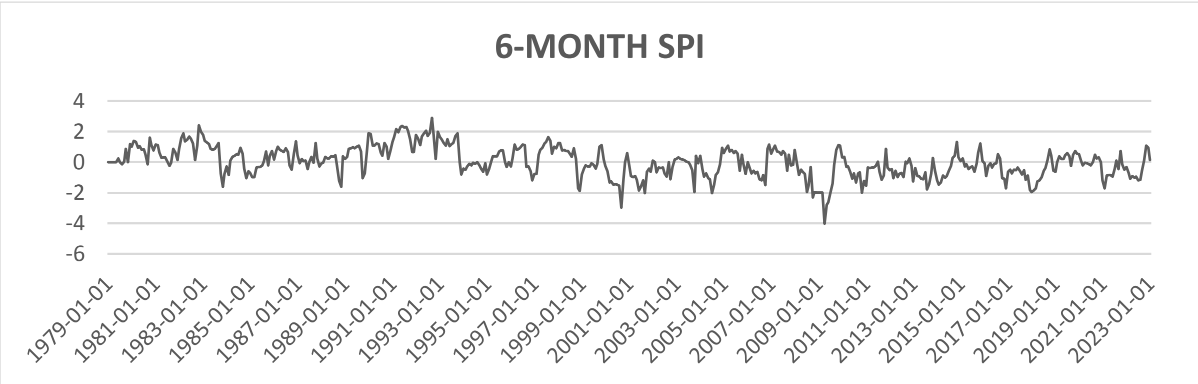

Figure 24: 6-Month SPI for Rabat-i-Akhand Station

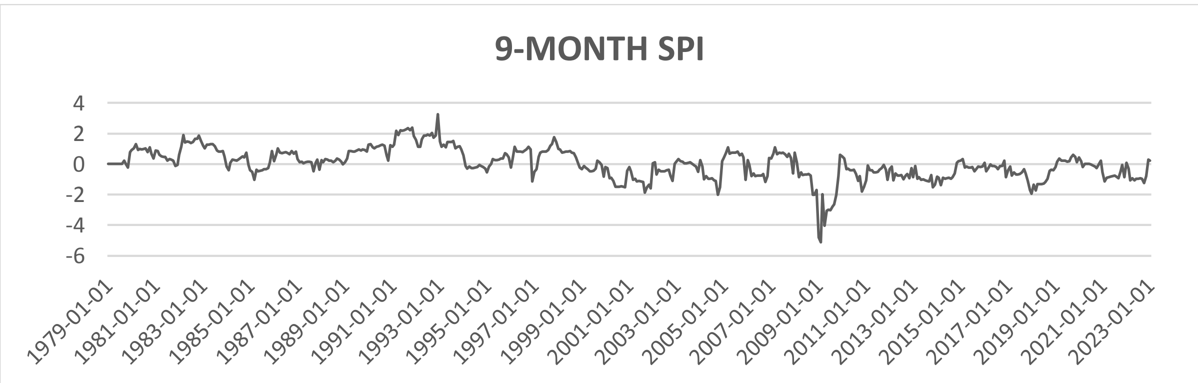

Figure 25: 9- Month SPI for Rabat-I Akhand station

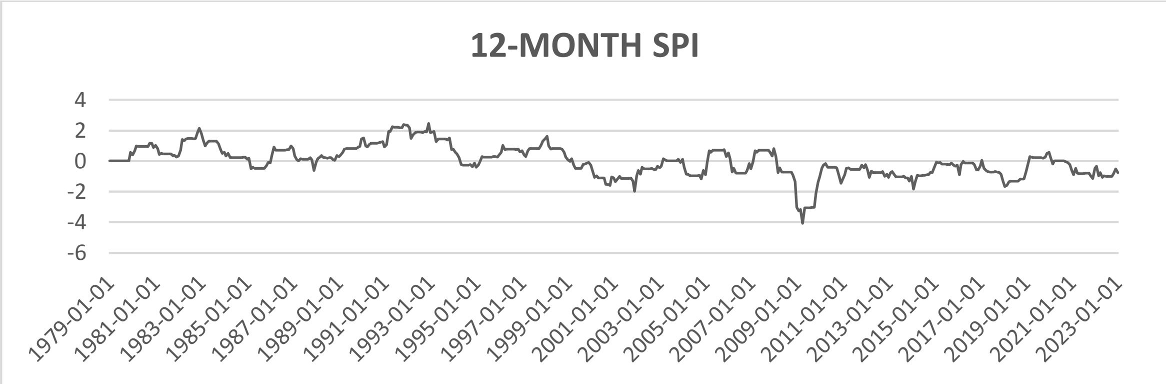

Figure 26: 12-Month SPI for Rabat Akhand-i- Station

Tagab Ghaza

As the results indicate, Tagab Ghaza station has experienced the most severe drought ever seen in History of Afghanistan in the past 43 years with the peak value in the start of the year 2009, which also coincide with international reports about the severe droughts in Afghanistan between year 2008 to 2009. This recorded SPI value for the 9-month SPI is -5.58, recorded in the year 2009. This extraordinarily low SPI value represents an unprecedented and extremely severe drought event, lasting for nine months. The occurrence of such an extreme drought in 2009 marks it as the most severe drought not only for the Tagab Ghaza station but also across all stations analyzed from 1979 to 2023. The most extremes value for the 1-month SPI is -2.71, noted in the year 2021. While this value indicates a short-term drought episode, it is considerably less severe compared to the 9-month SPI event in 2009. However, it still implies localized water stress and potential impacts on agricultural activities in the vicinity of the station. The most extremes value for the 6-month SPI is -4.59, recorded in the year 2009. This highlights a prolonged drought period of six months, resulting in significant water scarcity and ecological challenges in the station's surroundings. The most extremes value for the 12-month SPI is -4.59, also observed in the year 2009. This aligns with the findings for the 6-month SPI, indicating a year-long drought event, reinforcing the severity and prolonged nature of the drought conditions experienced during that year. The result of Table 2 and 3 shows that the station has experienced 9 and 15 times of extreme drought for the past 43 years with 1-month and 6-month SPI respectively, which is the highest number across all station in Herat. The station has also experienced 5.83 and 10.91 years of drought in the past 43 years with 1-month and 6-month SPI Respectively.

The SPI analysis underscores the exceptional nature of the drought events at the Tagab Ghaza station, particularly the unprecedentedly low SPI value of -5.58 in 2009. This extreme drought event likely had far-reaching consequences on agriculture, water resources, and communities in the region. Understanding such extreme drought occurrences is crucial for implementing robust drought mitigation strategies, water resource management plans, and sustainable development initiatives to enhance the resilience of the Tagab Ghaza area to future drought events.

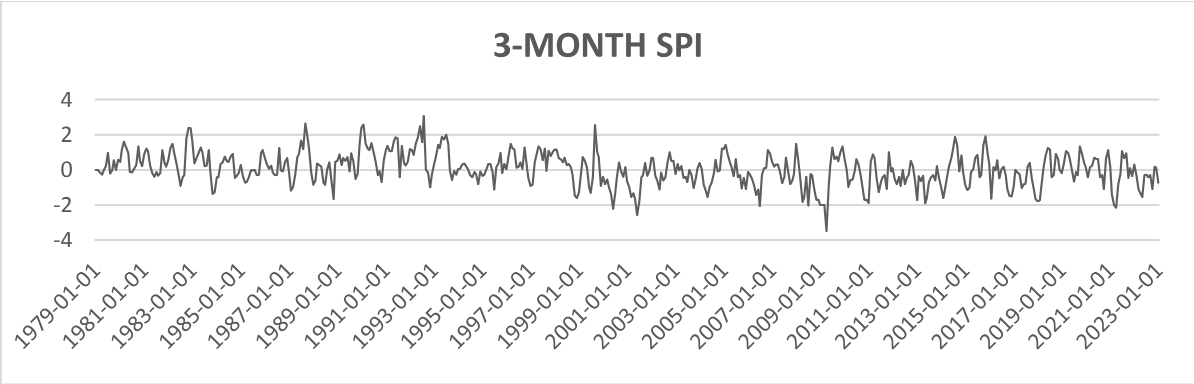

Figure 27: 3- Month SPI for Tagab Ghaza station

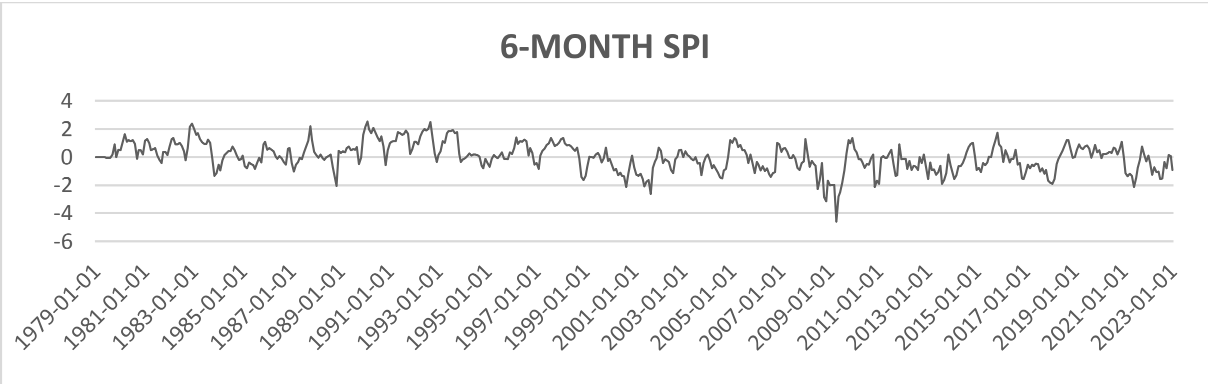

Figure 28: 6-Month SPI for Tagab Ghaza Station

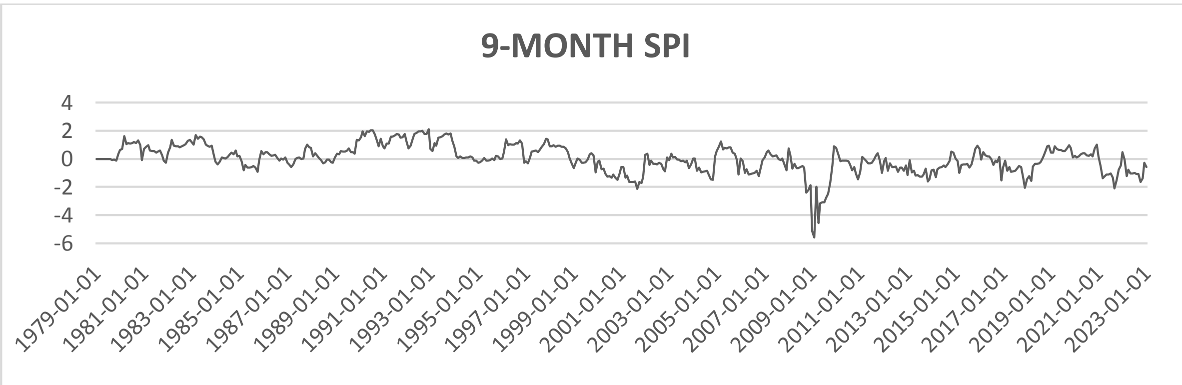

Figure 29: 9- Month SPI for Tagab Ghaza station

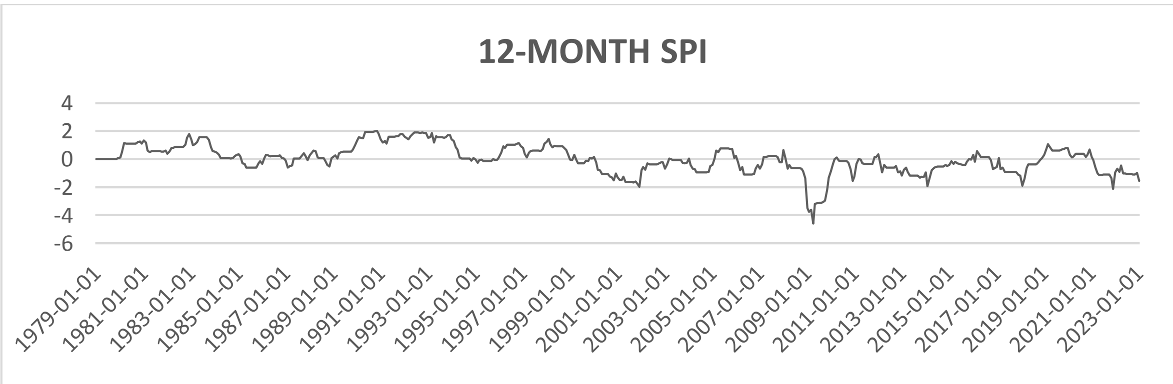

Figure 30: 12-Month SPI for Tagab Ghaza Station

Discussion

2001 drought

The analysis of the Standardized Precipitation Index (SPI) across all stations provides valuable insights into the occurrence of meteorological droughts in the region of Herat. Among the recorded data, the year 2001 stands out as a particularly extreme drought year, evidenced by a SPI value of -2. This drought event is not only widespread across all five stations in this research but also consistently reported in other studies conducted both within Afghanistan and neighboring countries such as Iran and Pakistan. This finding aligns perfectly with the report from The Asia-Pacific Network for Global Change Research, which identifies 2001 as the worst drought year in recorded Afghan history (APN, 2015). The impact of this severe drought extended beyond Afghanistan, affecting neighboring countries as well, and putting around 3.8 million people at risk of famine (CNN, 2023). However, the most severe and unparalleled drought event in Herat occurred in 2009. During this period, SPI values plummeted to as low as -5.58 for Tagab Ghaza and -5.11 for Rabad-i-Aghund, spanning over a duration of 9 months. These figures indicate that the most extreme droughts ever witnessed in Afghanistan happened at these two stations, with SPI values even surpassing those recorded during the notorious drought of 2001.

2008- 2010 drought

Focusing on the drought events at Tagab Ghaza and Rabad-i-Aghund stations, it is evident that the drought at Tagab Ghaza persisted for a daunting 14 months, starting in October 2008 and subsiding in December 2009, with a peak SPI value of -5.58 and an average SPI value of -2.89. Similarly, the drought at Rabad-i-Aghund endured for the same duration, with a peak SPI value of -5.11 and an average SPI value of -2.79. These findings are in line with reports from various governmental and non-governmental organizations that have highlighted the severity and impact of drought during the period from 2008 to 2010. For example, according to the United States Department of Agriculture, severe drought caused a major decline in the 2008/09 Wheat Production (Usda.gov, 2023). Additionally, a report by NASA stated that "in 2008, drought struck Afghanistan and nearly destroyed the country's winter grain crop" (Earthobservatory.nasa.gov, 2009).

Addressing the disparity in findings between this study and that of other researchers; for example, Alami's analysis of drought using the SPI model in five stations within the Helmand river basin and Kabul river basin, as well as Nostrati's study in Azarbaijan province, which shares a border with Herat province, did not report drought occurrences during the same years. The explanation for this discrepancy lies in the diverse weather conditions across Afghanistan. To accurately predict drought, it is essential to conduct localized analyses for each specific location. As demonstrated by our investigation of six different stations, the absence of drought signs in the remaining three stations between the years 2008 to 2010 reaffirms the need for localized assessments.

Frequency and duration

As previously discussed in Table 3 and 2, which present the duration and frequency of drought occurrences over the past 43 years across various stations and time scales respectively, we observe an interesting trend. As the time scale increases, the duration and frequency of drought also shows an upward trend until the 6-month time scale, after which it experiences a slight decline. This finding suggests that prolonged droughts were more likely to occur when using longer time scales. For instance, the Cheldkhtaran station experienced 7 instances of extreme drought with 1-month SPI and 20 instances with 6-month SPI, indicating the higher likelihood of prolonged drought events when analyzing longer time frames. Based on Table 3, Cheldkhtaran and Khosh Rabat stations both l have experienced a substantial number of drought events in the past 43 years, totaling 12.25 years and 11.33 years, respectively. These durations encompass both moderate and severe droughts. Similarly, Pul-i-Hashemi and Tagab Ghaza stations have recorded 10.16 years and 8.5 years of drought, respectively. Notably, Nazdi-i-Herat and Rabat-I-Akhund stations have the highest rate of drought occurrence, enduring 11.91 years and 11.58 years, respectively, representing almost 27% of their time in drought conditions.

2018-2021 droughts

Though there have not been research to use SPI or any other model in the recent year to address the droughts that we experienced in year 2018 and 2021, there have been various governmental and non- governmental organization that highlighted the severity of these. The 2018 drought impacted 22 out of 34 Afghanistan provinces and led to 13.5 million people facing heightened levels of food insecurity (Borgen Project, 2021). The findings of this study provide valuable confirmation of the occurrence of drought in these particular years, aligning with Table 1, which identifies them as among the years with the most severe droughts. According to the finding of this study, Nazdi-i-Herat, Pul-i-Hashemi, Rabat-i-Akhund, and Tagab Ghaza stations has experienced their most severe droughts in history in the year 2021 for 1-month SPI. And the year 2018 for multiple time scale is the year that Cheldkhtaran station has experienced its most severe droughts.

	Extreme observed value of SPI (Wet condition)									
Station	**SPI 1**	**Year**	**SPI 3**	**Year**	**SPI 6**	**Year**	**SPI 9**	**Year**	**SPI 12**	**Year**
Cheldkhtaran	3.2	2010-07-01	3.77	2010-09-01	2.6	1991-05-01	2.55	1991-08-01	2.57	2020-01-01
Khosh Rabat	2.94	2015-09-01	3.19	2015-09-01	2.57	1991-06-01	2.75	1991-11-01	2.91	1992-01-01
Nazdik-i-Herat	3.31	1999-09-01	3.46	2012-09-01	2.57	1991-05-01	2.53	1991-08-01	2.66	1992-01-01
Pul-i-Hashemi	3.11	1999-09-01	3.13	2013-08-01	2.32	1992-12-01	2.65	1992-12-01	2.49	1992-01-01
Rabat-i-Akhund	3.17	1999-09-01	3.66	1999-09-01	2.89	1992-09-01	3.25	1992-12-01	2.46	1992-12-01
Tagab Ghaza	3.04	1992-06-01	3.08	1992-08-01	2.53	1990-02-01	2.1	1992-12-01	2	1990-11-01

Table 4: The characteristics of extreme wet condition using SPI time-scales

Conclusion

The following conclusion can be drawn from droughts in Herat province.

1. The absence of drought occurrences in Cheldkhtaran, Nazdik-i-Herat, and Khush Rabat stations during the year 2008-2009 suggests that localized analyses are crucial when studying drought patterns in the Herat region. This observation emphasizes the significant variability of drought occurrences across different locations within the area, necessitating a site-specific approach to effectively analyze and understand drought dynamics.The

common extreme drought year for all station is year 2000, but the most extreme drought year is 2009 which is seen in Rabat Akhund, and Tagab Ghaza stations with an unprecedented SPI value of -5.11 and -5.58 respectively.

2. It is evident that with an increase in the time scale, there is a corresponding escalation in duration, frequency and intensity of drought events across all stations.
3. The years 2000, 2001, 2009, 2018, and 2021 stand out as periods when extreme drought events not only occurred but also had far-reaching consequences, significantly impacting the entire country.
4. Over the course of the past 43 years, the Cheldkhtaran station experienced the highest rate of time in droughts, accounting for 28.5% of its total duration. Following closely behind, the Khosh Rabat station experienced droughts for 26.4% of its time, while the Nazdik-i-Herat station endured drought conditions for approximately 27.7%. The Pul-i-Hashemi station experienced 23.6% of its time in droughts, whereas the Rabat-i-Akhund station experienced droughts for 26.9% of its duration. Notably, the Tagab Ghaza station had the lowest rate, with droughts affecting 19.8% of its total time during the specified period. Collectively, the average percentage of time spent in drought, whether moderate or severe, across all stations was 25.5% over the past 43 years.

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