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Original Research Article

Meteorological Drought Assessment Analysis for Balkhab Sub–River Basin, Afghanistan

Homayoun Khoshnod[*1], *Azim Jan Zahid*[2], *Naqibullah Rahmani*[3], *Hasibullah Rahimi*[4]

[1]Faculty of Hydraulic structure in Integrated Water Resources Management, Polytechnical University of Kabul, Darulaman Road, Senatoriam, 6th District, Kabul, Afghanistan
e-mail: homayounkohsnod14@gmail.com
[2]Civil, Environmental and Architectural Engineering, Sungkyunkwan University, 25-2 Seonggyungwan-ro, Jongno District, Seoul, South Korea
e-mail: azimjan.zahed@gmail.com
[3]Remote Sensing and GIS, National Institute of Technology Warangal, National Institute of Technology Campus, Hanamkonda, Telangana 506004, India
e-mail: nrahmani@student.nitw.ac.in
[4]Disaster Risk Management, Kabul University, Kabul 100310, Afghanistan
e-mail: wrd.hasibrahimi1512@gmail.com

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ABSTRACT

This study investigates meteorological drought patterns in the Balkhab Sub River Basin (BSRB) from Oct-1981 to Sep-2024 using satellite-based Climate Hazards Group InfraRed Precipitation with Stations (CHIRPS) precipitation data and four drought indices: Normal-SPI, Log-SPI, SPI-12, and PNPI. Data from eight selected points across the basin were analyzed to evaluate drought severity, identify critical drought years, and assess spatial-temporal drought distribution. The CHIRPS data showed strong correlation with ground observations ($R^2 \approx 0.91$), confirming its reliability. The SPI-12 index effectively captured long-term droughts, while PNPI was sensitive to short-term variability. All indices identified 2001 as an extreme drought year across all points. Other significant drought years included 1985, 1986, 2022, and 2023. Spatial analysis indicated higher drought frequency in points R1, R2, R3, and R8. The study concludes that CHIRPS data, combined with multiple indices, offer a robust approach for drought monitoring in data-scarce regions, supporting future water resource planning and climate resilience strategies in BSRB.

KEYWORDS

Balkhab sub river basin, Drought indices, CHIRPS precipitation, SPI, PNPI

INTRODUCTION

Drought is often viewed as a purely meteorological event, and the severity of past dry periods can be assessed by combining consecutive monthly index values using an objective method. This approach categorizes drought severity into four distinct levels: mild, moderate, severe, and extreme [1]. Drought can develop in both high- and low-rainfall regions. It represents a departure from the long-term average relationship between precipitation and evapotranspiration for a given location—a balance that is typically considered ‘normal’ for that area [2].

Since the 1970s, Afghanistan has experienced a rise in both the frequency and intensity of droughts, significantly impacting agriculture and overall socio-economic stability [3]. This national trend is particularly evident in northern provinces such as Balkh, Jawzjan, and Faryab, which are increasingly vulnerable to the impacts of climate change. These regions are facing prolonged droughts, reduced water availability, and rising temperatures [4]. Such climatic shifts threaten agriculture, food security, and local ecosystems, placing significant pressure on communities. Without effective adaptation and resource management, environmental stresses in the region are likely to intensify.

Temperatures are projected to continue rising until at least mid-century under all emissions scenarios, and without significant reductions in greenhouse gas emissions, global warming is expected to exceed 1.5 °C and potentially 2 °C within this century. By 2100, global temperatures are anticipated to rise above 1.0°C across all scenarios relative to the pre-industrial baseline (1850–1900) and could surpass 3.0 °C or even 5.0 °C under high-emission pathways such as Shared Socioeconomic Pathway 5 + Radiative Forcing 8.5 W/m^2 (SSP5-8.5), the SSP5-8.5 is a high-emission, fossil-fuel–driven scenario in the IPCC climate models that results in strong radiative forcing (8.5 W/m^2) and the highest projected global warming levels by 2100 [5,6].

These global climate trends are already manifesting in countries like Afghanistan, where the impacts are particularly severe. Afghanistan experiences high variability in precipitation and frequent droughts, with projections indicating a likely reduction in annual rainfall—especially in the western and northern regions—posing serious risks to water resources and agricultural productivity [7]. Observed climate trends across South and Central Asia further confirm increased rainfall variability and a higher frequency of droughts in Afghanistan. Climate models suggest a future decline in overall precipitation, shifts in seasonal rainfall patterns, longer dry spells, and more intense short-term rainfall events [5].

In particular, precipitation is expected to decrease during critical agricultural periods such as spring, leading to prolonged droughts. These changes will significantly affect farming communities and intensify water stress in both rural and urban areas [8]. Between 2024 and 2030, Afghanistan is projected to face rising temperatures, increasingly erratic rainfall, and extended droughts, all of which will have major implications for water availability and food security across the country [9–12].

These anticipated climate shifts further highlight the importance of localized drought assessment and monitoring. Due to Afghanistan's location in an arid climate zone with highly variable weather patterns, accurately assessing meteorological drought is crucial for effective water resource management [13]. In the Northern River Basin, meteorological drought has been analyzed using the Standardized Precipitation Index (SPI) over various time scales (SPI-1, SPI-3, SPI-6, SPI-9, and SPI-12), utilizing observational data from 12 hydrometeorological stations from 1979 to 2022. The results reveal that the basin experienced extreme drought conditions in the years 2000 and 2001 [14], underscoring the region's vulnerability and the need for adaptive planning.

However, based on the literature review, meteorological drought analysis in the Northern River Basin—particularly in the Balkh sub-basin—has not been thoroughly conducted using multiple drought indices and satellite data comparison. A major gap in this study area is whether CHIRPS satellite precipitation data can be effectively applied in this basin. Therefore, it is necessary to investigate and compare drought severity using CHIRPS data at eight locations within the sub-basin, alongside the application of four different drought indices.

METHODS AND MATERIALS

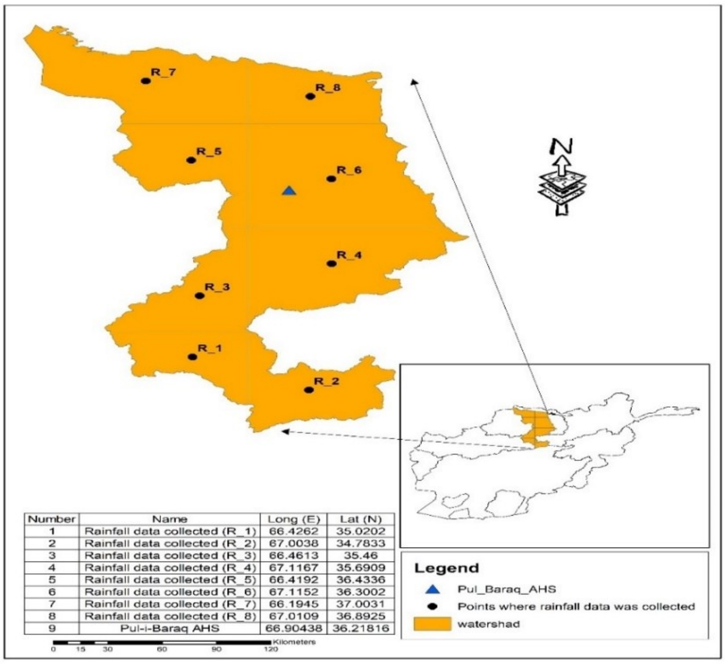
The materials and methods of this study are presented below, form section 2.1 to section 3.

Study area

Afghanistan's hydrological system is divided into five main river basins—Kabul, Helmand, Harirud-Murghab, Northern, and Amu Darya or Panj-i-Amu—according to its geological features and hydrological structure [15]. The Northern River Basin (NRB) of Afghanistan is further divided into five primary sub-basins: Khulm Aibak, Balkhab, upper Sari Pul, Lower Sari Pul and Shirin Tagab Sub River Basin [16,17]. The main focus of this study is on the Balkhab sub river basin (BSRB), utilizing CHIRPS satellite data for analysis.

To ensure the accuracy of satellite-derived precipitation data, it is essential to compare it with reliable ground-based observations. Therefore, an active hydro-meteorological station within the BSRB was selected as a reference point. The Pul-i-Baraq Hydro-meteorological station, installed in 2008 by the Ministry of Energy and Water of Afghanistan, serves this purpose well. Operating continuously with automated hourly recordings, this station provides robust and reliable rainfall data.

Located near the R-6 point and close to the center of the BSRB (as shown in Figure 1), the Pul-i-Baraq station offers representative precipitation data for the basin. Consequently, the study confidently uses the data from this station to validate the CHIRPS satellite estimates and achieve its research objectives.



Number	Name	Long (E)	Lat (N)
1	Rainfall data collected (R_1)	66.4262	35.0202
2	Rainfall data collected (R_2)	67.0038	34.7833
3	Rainfall data collected (R_3)	66.4613	35.46
4	Rainfall data collected (R_4)	67.1167	35.6909
5	Rainfall data collected (R_5)	66.4192	36.4336
6	Rainfall data collected (R_6)	67.1152	36.3002
7	Rainfall data collected (R_7)	66.1945	37.0031
8	Rainfall data collected (R_8)	67.0109	36.8925
9	Pul-i-Baraq AHS	66.90438	36.21816

Figure 1. Balkhab Sub River Basin with precipitation points including CHIRPS and observed data

Data

To achieve the objectives of this study, daily precipitation data were required for the Balkhab Sub River Basin. For this purpose, 43 water years (1982 to 2024) of precipitation in millimeters (mm) were extracted from the CHIRPS website using the Google Earth Engine platform. To ensure the reliability and accuracy of the satellite-based CHIRPS data, observational data from the Pul-i-Baraq hydrometeorological station, obtained from the Ministry of Energy and Water (MEW) [18], were also used for comparison. The average precipitation values were calculated from eight selected CHIRPS points across the Balkh Ab catchment, alongside measurements from the Pul-i-Baraq station, which was installed by MEW and has been actively recording since 2008 (Figure 1).

In support of this analysis, MEW has recently filled gaps in precipitation data for the country's meteorological network [19], enhancing data continuity and completeness.

Furthermore, the study incorporated reanalyzed (gap-filled) data from 1979 to 2008, developed with technical assistance from the JICA-HYMEP project [20]. It is also important to highlight that Pul-i-Baraq hydrometeorological station records precipitation every 15 min, which is later processed into daily values through MEW's quality control procedures. Detailed specifications regarding the data scale and sources used are presented in **Table 1** and illustrated in Figure 2.

Table 1. Showing Specifications of data used [20,21]

No	Data	Source	Observed Range	From	To
1	Precipitation (mm)	CHIRPS	Daily	1/Oct/1981	30/Sep/2024
2	Precipitation (mm)	MEW	Daily	1/Oct/1981	30/Sep/2024

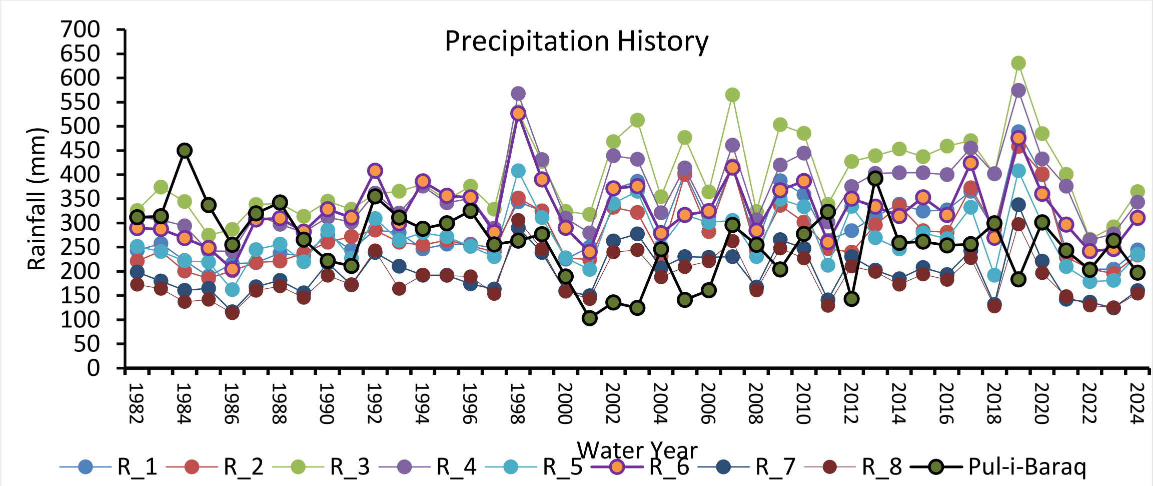


Figure 2. The annual average precipitation data from CHIRPS (points R_1 to R_8) and observational data from the Pul-i-Baraq AHS station

As shown in **Table 2**, the analysis of rainfall data indicates that the highest average rainfall is at point R-3 with 394 mm, while the lowest is at point R-8 with 187 mm. The maximum satellite-recorded rainfall is also at R-3 (631 mm), and the lowest is at R-8 with 114 mm. The highest variation (standard deviation) is found at R-3, indicating significant fluctuations in rainfall at this location. Observational data from the Pul-i-Baraq station show an average rainfall of 259 mm, a maximum of 449 mm, and a standard deviation of 73 mm.

Table 2. Rainfall characteristics at eight points (R_1 to R_8) based on CHIRPS data and observed data from the Pul-i-Baraq AHS station

Rainfall Characteristics	R_1	R_2	R_3	R_4	R_5	R_6	R_7	R_8	Pul-i-Baraq
Mean (mm)	291	276	394	361	268	327	198	187	259
Minimum (mm)	190	186	266	241	162	205	117	114	103
Maximum (mm)	489	458	631	574	408	526	338	306	449
Standard deviation (mm)	68	65	83	77	58	65	48	46	73

These results highlight notable spatial differences in rainfall patterns across the Balkhab sub-river basin, emphasizing the variability between upstream and downstream areas. Such variations are critical for understanding local water availability and planning for effective water resource management. This spatial insight also underlines the importance of using both satellite and ground-based observations for accurate hydrological assessments in semi-arid regions like northern Afghanistan.

In this study, the 12-month Standardized Precipitation Index (SPI-12) for September, along with the Normal-SPI, Log-SPI, and Percent of Normal (PN) methods, were applied to evaluate meteorological drought conditions at eight selected points within the Balkh-Ab catchment, located in the Northern River Basin. CHIRPS precipitation data were used as the primary input for the analysis. Initially, spatial data processing and point selection were performed using ArcGIS, including the creation of fishnet grids and extraction of observation points. Subsequently, precipitation data were coded and analyzed using Google Earth and statistical tools to derive drought indices and determine their temporal evolution. The SPI values were calculated using SPI software, and the results were compared across all applied methods to identify the most suitable approach for drought assessment in this sub-river basin. The overall methodology is illustrated in **Figure 3**, which summarizes the sequential steps of data preparation, processing, analysis, and comparison of drought indices.

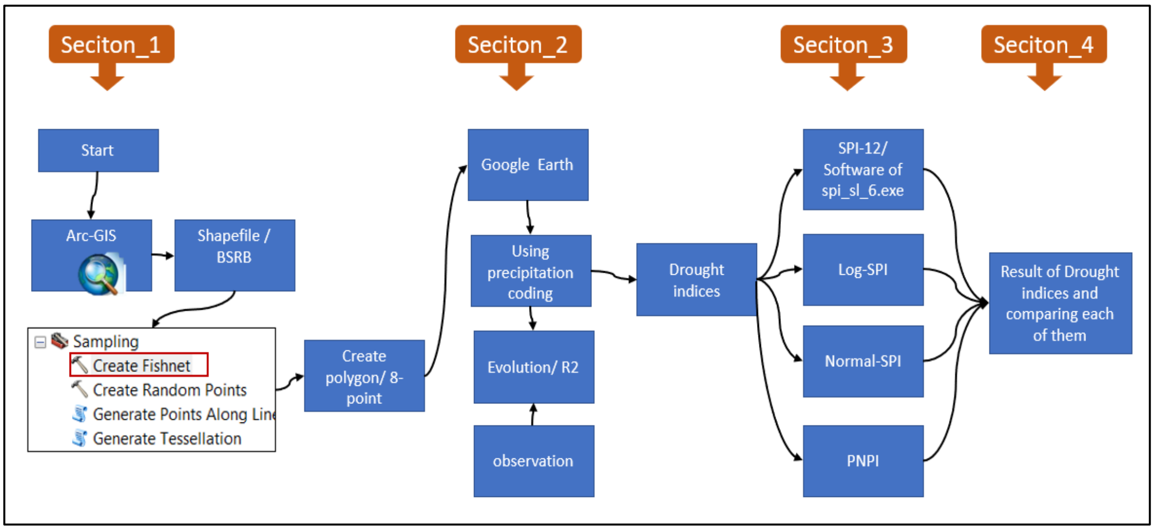


Figure 3. The overall of methodology in the study area

<u>Standardized precipitation index.</u> To provide a robust assessment of drought conditions in the Balkhab sub-river basin, the 12-month Standardized Precipitation Index (SPI) was selected as the primary metric. This index, introduced by McKee et al. in 1993, is widely recognized for its effectiveness in monitoring meteorological drought across various time scales, including short-term (1-, 3-, and 6-month) and long-term (12-month) periods [22]. The SPI works by standardizing precipitation data so that the mean is zero and the standard deviation is one, making it suitable for comparative analysis across different regions and timeframes [23]. Positive SPI values indicate wet conditions, while negative values represent varying degrees of drought. The severity of a drought is categorized based on SPI values, with events beginning when the index falls below -1.0 and ending when it returns to positive. Duration and intensity are determined using the cumulative monthly SPI values [24].

In this study, the SPI was calculated using dedicated SPI software, employing distributions such as normal, logarithmic, and gamma to assess precipitation anomalies. The 12-month SPI, in particular, helps reflect long-term climatic trends and aligns closely with the Palmer Drought Severity Index in many regions [25]. SPI adjusts for rainfall skewness by fitting a gamma distribution and converting precipitation to a standard normal scale, making it suitable for most drought analyses. Normal-SPI instead assumes rainfall is normally distributed, which can misrepresent extremes in regions with highly skewed. These calculated values, as illustrated in

Table 3, offer valuable insight into the temporal and spatial extent of drought events in the study area.

Table 3. Classification of SPI Value [25]

2.0+	Extremely Wet
1.5 to 1.99	Very Wet
1.0 to 1.49	Moderately Wet
-0.99 to 0.99	Near Normal
-1.0 to -1.49	Moderately Dry
-1.5 to -1.99	Severely Dry
-2 and less	Extremely Dry

Normal-SPI. The normal-SPI simplifies calculation by using the normal probability distribution instead of the gamma distribution, making it mathematically easier to compute [26]:

$$SPI = Z = \frac{x - \mu}{\sigma} \tag{1}$$

where z is the standardized value (the SPI value), μ is the mean of the data series, x is an individual value in the data series, and σ is the standard deviation of the data series.

Log-SPI. The log-SPI aims to detect meteorological droughts using a statistically appropriate method for non-negative and positively skewed rainfall data. It applies a log-normal distribution to transformed data for improved accuracy. Log-SPI reduces skewness by applying a logarithmic transformation before standardization, making it more reliable when gamma fitting is unstable or when rainfall is strongly asymmetric. This approach simplifies SPI calculation and enhances drought monitoring reliability, the SPI becomes:

$$SPI = Z = \frac{\ln(x) - \mu}{\sigma} \tag{2}$$

According to Formula 2, μ and σ are the mean and standard deviation of the log-data series, respectively.

Percent of Normal Precipitation Index. The basic concept of the Percent of Normal Precipitation Index (PNPI) is to express the ratio of actual precipitation to the long-term normal precipitation for a specified time period as a percentage. It can be calculated across various time scales, including weekly, monthly, seasonal, and annual [27]. At least 30 y of data is generally recommended for the PN method to ensure statistical validity and accurate drought assessment [28]. The PNPI index classifies values between 70–80 % as normal, 55–70 % as moderately dry, 40–55 % as severely dry, and less than 40 % as extremely dry [29].

METHOD OF EVALUATION

To evaluate the performance of satellite precipitation data, this study compared data from the Pol-e-Barq hydrological station (AHS) with satellite data at point R-6. Similarly, the accuracy and reliability of CHIRPS satellite precipitation data were assessed in the Haihe River Basin by comparing them with ground-based rainfall observations from 29 stations over various time scales. A comprehensive statistical evaluation was performed using standard performance metrics, including the correlation coefficient (CC), root mean square error (RMSE), relative bias (BIAS), mean error (ME), as well as categorical statistics such as probability of detection (POD), false alarm ratio (FAR), and critical success index (CSI) to better understand error levels and detection capabilities [30].

In line with these methods, our study applied RMSE, BIAS, R², and ME to compare satellite data with observational measurements. The specific calculation methods for these metrics are detailed in **Table 4**, providing a clear framework for assessing data accuracy and performance in this research. Ci represents the precipitation values estimated by CHIRPS, while Gi refers to the precipitation measured by ground-based gauges. The variable N indicates the total number of data samples.

Table 4. Metrics utilized in the present analysis **[30]**

Statistic metrics	Formula	Values range	Optimal value
RMSE	$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(C_i - G_i)^2}$	-1 to 1	1
BIAS	$BIAS = \frac{\sum_{i=1}^{N}(C_i - G_i}{\sum_{i=1}^{N} G_i}$	0 to α	0
ME	$ME = \frac{1}{N}\sum_{i=1}^{N}(C_i - G_i)$	-α to α	0

RESULT ON METHODOLOGY

As this study focuses on five core objectives, the following sections present a detailed analysis of the results corresponding to each of these key components.

Evolution of CHIRPS data

To begin, Table 3-1 presents a comparison between the 12-month average precipitation data obtained from ground-based observations and CHIRPS for the water year period of 1982–2024. The ground station data were derived by aggregating daily precipitation into 12-month totals. CHRIPS data from eight locations were used for comparison over the 45-y period in the Balkhab Sub River Basin. The table includes statistical indicators such as the coefficient of determination (R²), mean error (ME), bias (BIAS), and root mean square error (RMSE) to evaluate the agreement between satellite-based and observed precipitation.

CHIRPS exhibited a strong correlation with ground-based observations throughout the monthly from each year (**Table 5**), with an average R² of approximately 0.91, reflecting a high level of consistency. The mean error (ME) was around 9.13 mm, the RMSE was 9.14 mm, and the BIAS was approximately 3.54 %, suggesting that CHIRPS slightly overestimated precipitation but within acceptable limits. This discrepancy may be attributed to limitations in the satellite precipitation algorithms and the variability of the monsoon climate **[31]**.

Table 5. Statistical evaluation results at the yearly scale

RMSE (mm/12-months)	BIAS%	ME (mm/12 months)	R^2
9.14	3.54	9.13	0.91

These results confirm that the annual precipitation data from CHIRPS, with a higher R² value compared to the other three methods, has shown better performance in the point of R_6 satellite data with observed, making it a reliable source for estimating annual rainfall in the region. Accordingly, this study has utilized the R^2 value as a key metric in validating data sources used for meteorological drought analysis.

The correlation between CHIRPS satellite data at point R-6 and precipitation data from the Pul-i-Baraq AHS 43 y period is presented in **Figure 4**.

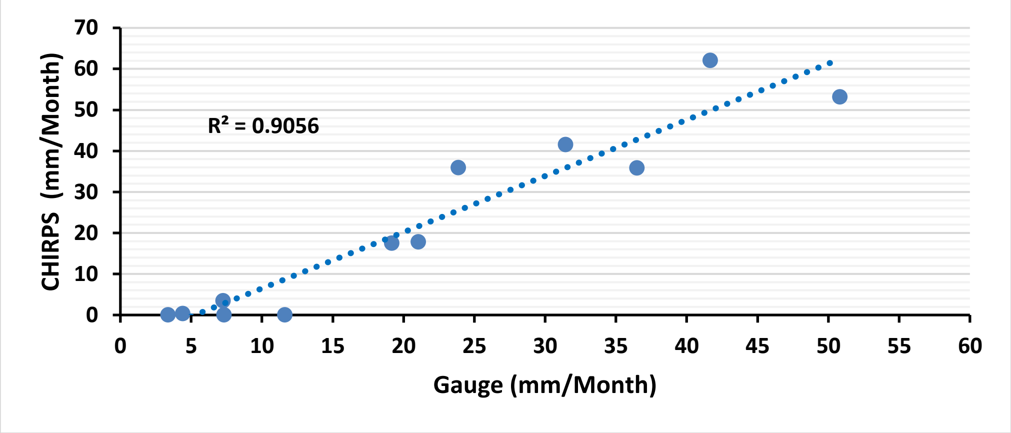


Figure 4. Scatter plot comparing the average monthly rainfall between Pul-i-Baraq AHS observations and CHIRPS satellite estimates at point R_6

SPI_12, September

Building upon the statistical analysis, **Figure 5** further illustrates the temporal variation in SPI-12 values across the eight selected points (R_1 to R_8) in the BSRB. The figure shows that in certain years, such as 2001, 2011, and 2021, there was a sharp decline in SPI-12 values, indicating the occurrence of severe to extreme droughts. Specifically, in 2001, all SPI values dropped below -2, clearly indicating an extreme drought event. In contrast, in years like 1998, 2005, and 2019, an increase in SPI values is observed, indicating wet periods during these years.

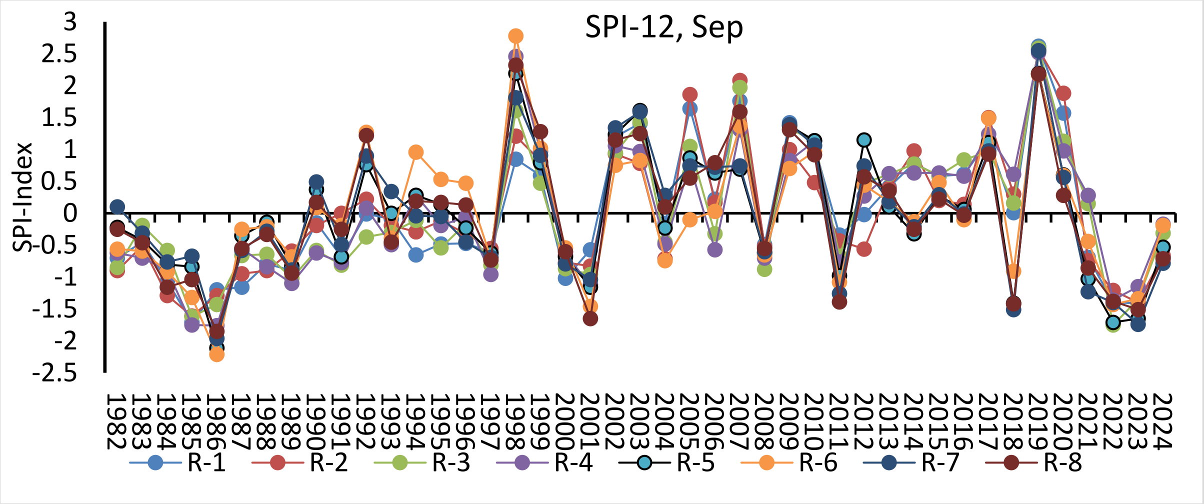


Figure 5. The results of SPI-12 for the month of Sep at points R_1 to R_8 in the study area

Furthermore, the relative consistency of SPI changes across different points (R_1 to R_8) suggests that CHIRPS satellite data displayed relatively similar behavior at all observed locations and simultaneously responded to precipitation changes across the region. This consistent trend strengthens the reliability of CHIRPS data in capturing drought dynamics across the basin.

Normal – SPI

Following the temporal analysis presented in **Figure 5**, and **Figure 6** further supports the findings through the Normal-SPI index. It highlights that the year 2001 experienced an extreme drought across all points, reinforcing the severity observed in earlier assessments. In addition, the SPI values in 1986, 2022 and 2023 dropped below -1.5 at most locations (R_1 to R_8), indicating widespread severe droughts during these years (**Figure 6**).

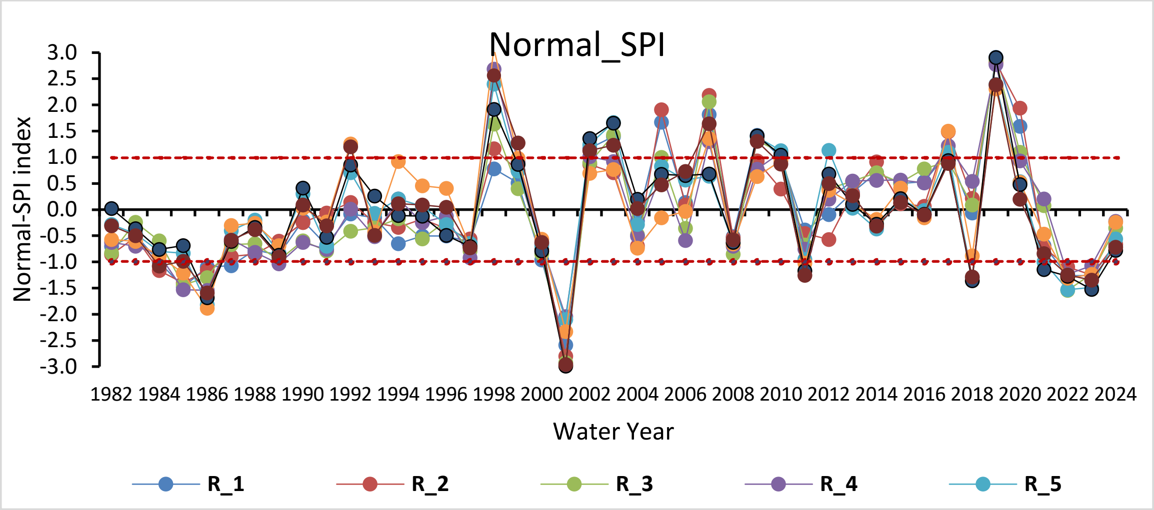


Figure 6. The results of Normal-SPI at points R_1 to R_8 in the study area

Conversely, wet conditions are evident in years like 1998,2005, and 2019, where SPI values increased significantly. The similarity in SPI trends across the selected points from Oct-1981 to Sep-2024 indicates strong temporal coherence, confirming the consistency of CHIRPS data in capturing regional drought and rainfall variability over time.

Log-SPI

Figure 7 presents the Log-SPI index for the period 1982 to 2024 across the same eight points (R_1 to R_8). This figure further confirms the occurrence of extreme drought conditions in 2001, where SPI values at all locations dropped below-2. The consistency of this result across multiple indices reinforces the severity of the drought that year.

Additionally, the Log-SPI index highlights other significant drought years such as 1985, 2022, and 2023, each showing sharply negative values indicative of widespread severe drought events. This continued agreement across different SPI calculations underscores the reliability of the CHIRPS dataset in detecting and monitoring drought variability in the eight points of BSRB.

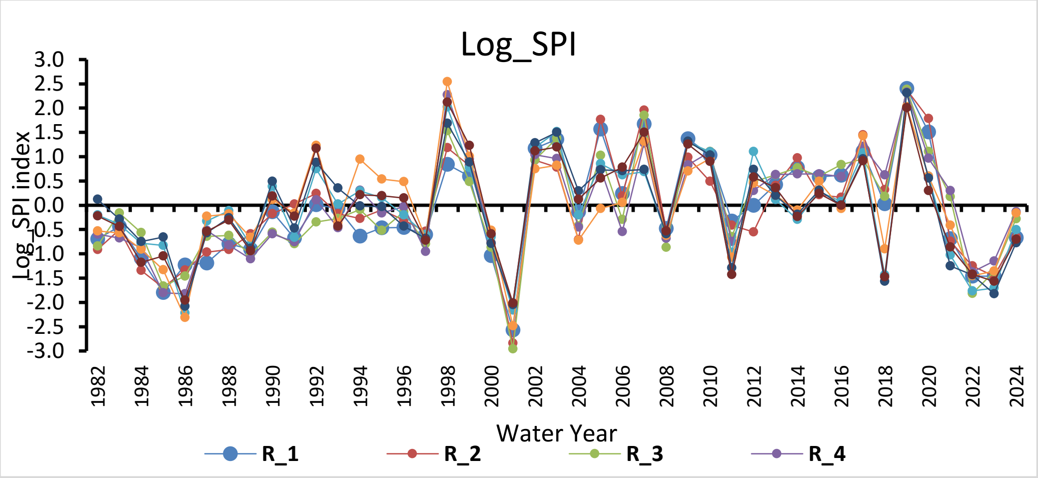


Figure 7. The analysis of Log-SPI values at locations R_1 through R_8 within the study area

PNPI

Continuing from the analysis of the Log-SPI index in **Figure 7**, **Figure 8** illustrates the behavior of the PNPI index across all eight (R_1 to R_6) points. The figure clearly shows that the year 2001 experienced a sharp decline in PNPI values, indicating an extreme drought event, consistent with previous indices.

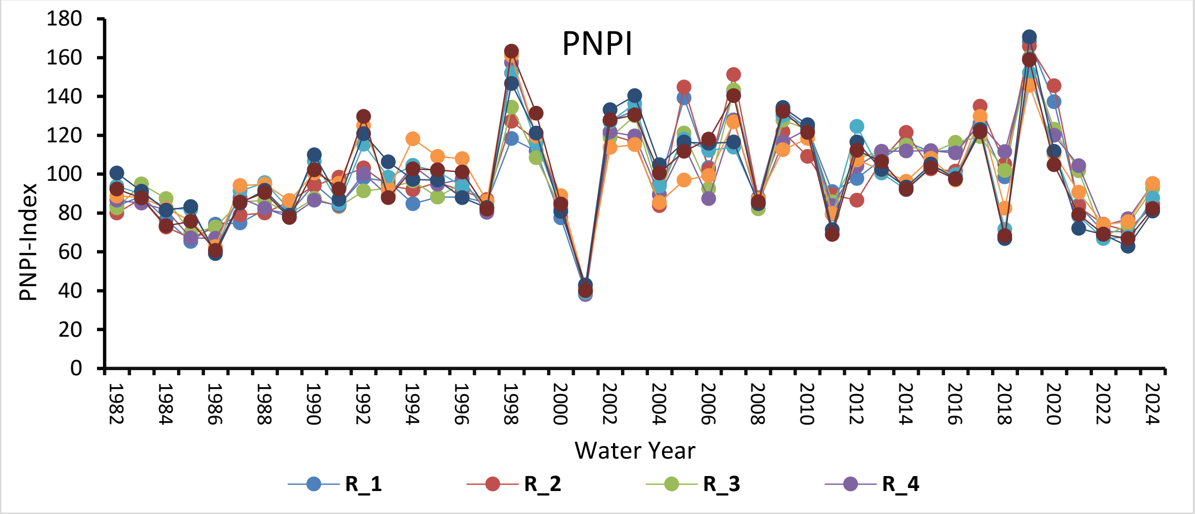


Figure 8. The results of PNPI at eight points in study area

Moreover, the years1998, 2005, and 2019 demonstrate a noticeable increase in SPI values, reflecting wet periods during those years. The consistency of these results across different SPI methods (Normal, Log, and SPI-12) further validates the robustness of CHIRPS satellite data for drought monitoring in the above-mentioned Points.

Drought indices in Balkhab sub river basin

Based on satellite data from 8 selected points in the BSRB, for the whole basin, the arithmetic mean of these points was used to determine the intensity and identify drought years. The average precipitation across these eight points over the 43 water years was approximately 287.7 mm. Meanwhile, in 2018, the Ministry of Energy and Water calculated the average precipitation for this sub-river basin using three methods—arithmetic mean, weighted mean, and Thiessen polygon—as 264.6 mm, 299.1 mm, and 248.6 mm, respectively **[32]**. For a more detailed analysis, precipitation data from the water years Oct-1981 to Sep-2024 were examined, and drought intensity across the basin was assessed using four drought indices.

The results, presented in two figures – **Figure 9** displaying indices (Normal-SPI, Log-SPI and SPI-12, Sep) and **Figure 10** showing the PNPI index—clearly indicate that the year 2001 was one of the driest years, experiencing extreme drought conditions across the BSRB. Both figures confirm this year as a period of extremely drought. These findings reflect strong consistency among different points within the basin and highlight the reliability of satellite data in detecting critical climatic conditions.

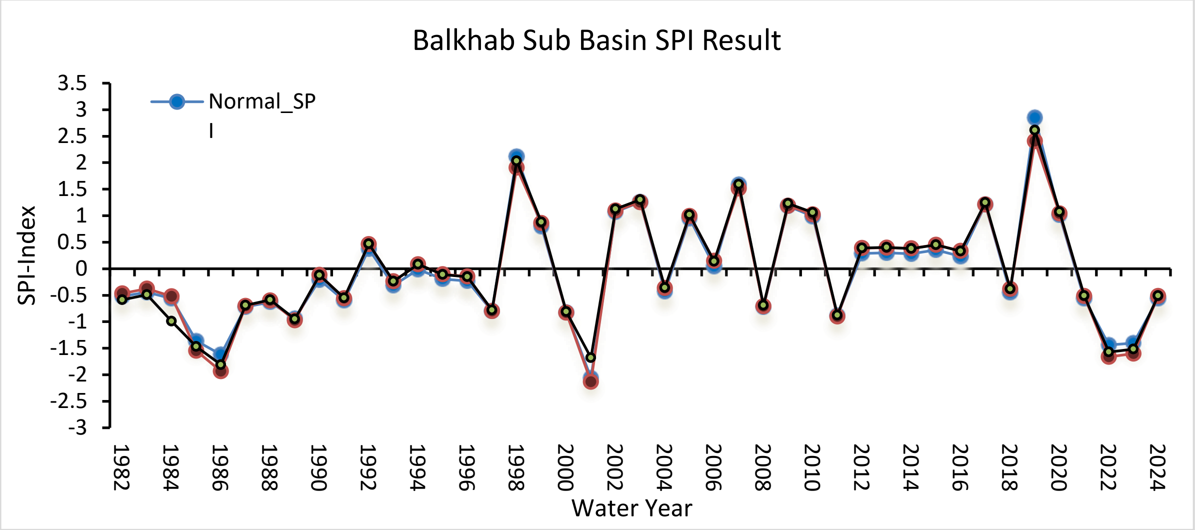


Figure 9. Presents the Normal_SPI, Log_SPI, and SPI_12 values for Sep in the (BSRB)

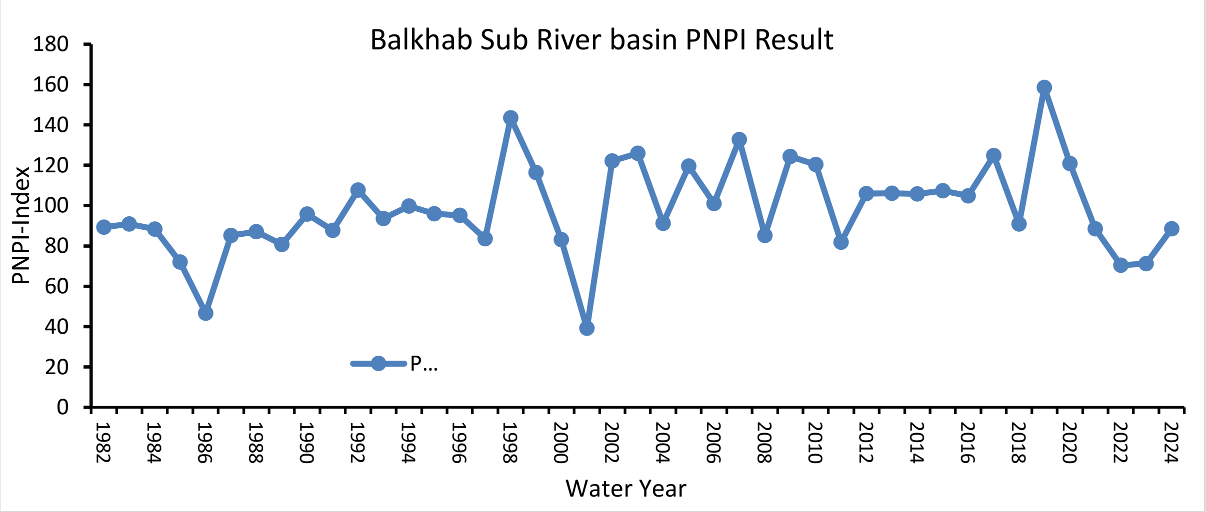


Figure 10. Showing the PNPI value in the BSRB

Since each of the three evaluation methods provides distinct insights into drought characteristics, the applying different methods allows for a more robust and comprehensive assessment of drought conditions. Minor differences observed among the drought indices are not merely methodological discrepancies; rather, they highlight subtle variations in drought intensity, onset, and duration that cannot be fully captured by a single approach. For instance, certain indices are more sensitive to extreme precipitation deficits, while others better represent moderate or prolonged drought conditions.

By applying all three methods, the robustness of drought characterization across different assessment methods are evaluated, ensuring that regions with highly skewed or below average distributed precipitation are adequately represented. These subtle but systematic differences among the indices provide valuable information on the temporal evolution and severity of drought events, thereby enhancing the reliability and interpretability of the results.

DISCUSSIONS ON RESULTS

To provide a more integrated understanding of drought patterns at the satellite-derived points and across the entire BSRB, the following paragraphs analyze the spatial and temporal behavior of drought events using multiple indices at selected locations within the BSRB.

A scientific analysis of meteorological drought in the Balkhab Basin was conducted using four indices: Normal SPI, Log-SPI, SPI-12 Sep and PNPI over the water years 1982 to 2024 at eight points (R1 to R8) within the basin. The results presented in **Table 6** illustrate drought trends, critical years, and the performance of each index in identifying various drought intensities.

This comprehensive assessment highlights the year 2001 as an "extreme drought" year across all points and indices, indicating widespread climatic stress in the basin. Additionally, recurring droughts in years such as 1985, 1986, 2022, and 2023 reflect multiple phases of moderate to severe droughts impacting different parts of the basin.

Across the entire BSRB, **Tables 6** and **7** present drought indices conditions for the water years 1982–2024 based on four different drought indices. Using monthly satellite-based precipitation data from CHIRPS, the analyses indicate that all drought indices performed well across the study area. Although each index exhibits distinct characteristics, their consistent behavior throughout the basin highlights the importance of employing multiple drought indices to provide a more accurate and comprehensive assessment of the climatic conditions of the BSRB.

In general, the southern part of the BSRB has a higher elevation than the northern part (**Figure 1**). As elevation increases within the basin, precipitation amounts also tend to increase, although the type and spatial pattern of precipitation vary across different locations. Moreover, the results show a significant decrease in precipitation in recent years in most parts of the basin, indicating the occurrence of severe and widespread climatic drought events across the BSRB, as well as the repetition and persistence of drought periods over recent decades. The overlap of results from the indices demonstrates the accuracy of CHIRPS satellite data in detecting temporal and spatial drought patterns in this sub-basin. This agreement among the indices confirms the importance and effectiveness of using satellite data for monitoring climate changes and planning water resource management in the region. Therefore, employing these indices in drought studies plays a crucial role in providing a more precise and comprehensive picture of the region's climatic conditions.

CONCLUSION

This study provides a comprehensive analysis of meteorological drought in the Balkhab Sub River Basin (BSRB) over a 43-year period (1982–2024), using satellite-based CHIRPS data and four drought indices: Normal-SPI, Log-SPI, SPI-12 Sep, and PNPI. Eight reference points (R1–R8) were selected across the basin to ensure spatial representation. The study aimed to assess drought intensity, identify critical drought years, evaluate the reliability of CHIRPS data, and compare index performance.

The CHIRPS data, verified against ground station observations at Pul-i-Baraq, showed a high correlation ($R^2 \approx 0.91$), confirming the satellite dataset's accuracy for regional drought monitoring. Among the indices, SPI-12 demonstrated the strongest capacity for identifying long-term droughts, effectively capturing major events in 1986, 2001, and 2023. The PNPI, being more sensitive to short-term variability, revealed localized and short-lived droughts, especially in points R6 and R8. The Normal and Log SPI also performed well in detecting medium-term drought patterns.

All indices unanimously identified the year 2001 as an extreme drought across the entire basin. Other notable drought years included 1985, 1986, 2022, and 2023, suggesting an increasing frequency of drought events in recent decades. Spatially, points like R1, R2, R3, and R8 experienced higher drought frequency, possibly due to topographic or climatic variability. The analysis outcomes can guide drought mitigation, inform policy and resource allocation, raise public awareness, and serve as a baseline for future drought prediction and early warning systems.

Table 6. Summary of the indicated droughts by the four methods

Rainfall data Point	Normal-SPI			Log-SPI			SPI_12, Sep			PNPI		
	Moderately Dry	Severely Dry	Extremely Dry	Moderately Dry	Severely Dry	Extremely Dry	Moderately Dry	Severely Dry	Extremely Dry	Moderately Dry	Severely Dry	Extremely Dry
R_1	1984–1987, 2022–2023	-	2001	1984–1987, 2000, 2022, 2023	1985	2001	1986, 1987, 2022, 2023	1985, 2021	2001	1985, 2023		2001
R_2	1984–1986, 2022–2023	-	2001	1984,1986, 2022, 2023	1985	2001	1982,1984,1986, 1987, 2021, 2022	1985, 2023	2001	1985		2001
R_3	1985, 1986, 2023	2022	2001	1985,1986, 2023	1985, 2022	2001	1986, 1987, 1990, 1995, 2000, 2008, 2021, 2022	1985, 2023	2001	1985, 2022	2001	
R_4	1989, 2022, 2023	1985, 1986	2001	1989,2022, 2023	1985, 1986	2001	1983, 1986–1989, 1995, 2008, 2023		1985, 2001	1985, 1986		2001
R_5	2018, 2023	1986, 2022	2001	2018, 2021	2022, 2023	1986, 2001	1985, 2008, 2022	1986	2001, 2021, 2023	1986, 2022, 2023		2001
R_6	1986, 2022, 2023	1986	2001	1985, 2011, 2022, 2023	-	1986, 2001	1983, 2008	1985, 1986, 2021, 2022	2001	1986	2001	
R_7	2011, 2018, 2021, 2022	1986, 2023	2001	2011, 2021, 2022	2018, 2023	1986, 2001	2000, 2008	1986, 2021	2001, 2023	1986, 2018, 2022, 2023		2001
R_8	1984, 2011, 2018, 2022, 2023	1986	2001	1984, 1985, 2011, 2018, 2022	1986, 2023	2001	1985, 1986, 2008	2021	2001, 2023	1986, 2011, 2018, 2022, 2023		2001

Table 7. Summary of the indicated droughts by the four methods in BSRB

River Basin	Normal-SPI			Log-SPI			SPI_12, Sep			PNPI		
	Moderately Dry	Severely Dry	Extremely Dry	Moderately Dry	Severely Dry	Extremely Dry	Moderately Dry	Severely Dry	Extremely Dry	Moderately Dry	Severely Dry	Extremely Dry
Balkhab Sub River basin	1985, 2022, 2023	1986	2001	-	1985, 1986, 2023, 2023	2001	1986, 1987, 2008, 2022	1985, 2021, 2023	2001	2022	1986	2001

The overall results confirm that CHIRPS satellite data, combined with multiple drought indices, provide a reliable and practical tool for drought assessment in BSRB. The findings highlight the growing risk of drought under changing climatic conditions and emphasize the need for proactive water management and climate adaptation strategies in the BSRB.

NOMENCLATURE

Symbols

L	length	[m]
P	pressure	[kPa]

Greek letters

ρ	density	[kg/m^3]

Subscripts and superscripts

ext	external
int	internal

Abbreviations

GDP	Gross Domestic Product
GHG	Greenhouse Gas

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