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A Comparison of the Frequency and Intensity of Standardized Precipitation Index (SPI) and the Rainfall Anomaly Index (RAI) during the Meteorological Drought across Harohar-Punpun Basin (India)

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

The term "drought" applies to a prolonged period when there is a water shortage because of insufficient precipitation, an excessive rate of evaporation, and excessive use of water from reservoirs and other storage, including ground water. It is a slow-onset phenomenon that can have significant social, economic, and environmental impacts. Both the frequency and severity of droughts are increasing globally due to manmade and natural factors. This study looked at how well SPIs (3, 6, 12-month time scales) and RAI (Rainfall Anomaly Index) performed at identifying drought occurrences over a period of 70 years (1951 to 2021) in India's Agro-Ecological Zones. The RAI and SPI values were computed using rainfall data from 9 meteorological stations located throughout the Harohar- Punpun Basin. According to the results, the RAI is more capable than SPIs in detecting historical records of actual occurrences. Additionally, RAI is more effective than SPIs for determining both short- and long-term droughts. Since RAI can better capture the true nature of the drought situation in the Harohar-Punpun Basin, it appears to be more responsive to drought circumstances. The primary causes of drought, according to the study, include minor variations in precipitation, willful ground water removal, changing cropping patterns, and substantial changes in land use. Regional planners and administrators will surely find use for this scientific study and integrated watershed management methods for sustainable water resource management, particularly for this region.

Keywords Meteorological drought; SPI (Standardized Precipitation Index); RAI (Rainfall Anomaly Index); Harohar- Punpun Basin.

1. INTRODUCTION

Drought is indeed a prolonged period of dryness and water scarcity that affects various parts of the Earth's system, including the atmosphere, lithosphere, and hydrosphere. It is considered one of the most severe climatic events. Drought occurs when hydrological and meteorological conditions result in a deficit of water supply compared to the normal or expected conditions [1]. arid areas are generally more prone to drought compared to other regions. This is because arid regions naturally have low levels of precipitation and limited water availability. Unlike tropical wet and humid regions, where rainfall is relatively consistent throughout the year, arid areas depend on sporadic and often infrequent rainfall events to sustain their water supply [2]. According to Bhunia et al. [3] this extreme climatic event has typically been divided into four categories: hydrological drought, agricultural drought, meteorological drought, and socioeconomic drought. When the decrease in rainfall for a given time frame a day, a month, a season, or an entire year—falls below a predetermined threshold, which is typically outlined as a percentage of the long-term average, it is experiencing a meteorological drought. According to Selvaraju and Baas [4], it usually refers to a long-term deviation from regular precipitation. According to the Indian Meteorological Department, meteorological drought occurs when rainfall over an area during the south-west monsoon season (June to September) is less than 25% of the average. For carrying out proper management of water resources, a scientific research and study are urgently required to determine the drought occurrence rate, magnitude, probable return period, and recurrence interval of severe and intense drought episodes [3]. According to the Intergovernmental Panel on Climate Change's 2007 report [5], the average surface temperature of the Earth has risen by around 0.76°C during the previous century. By the 2080s, India's temperature is expected to climb by 2.7–4.3 °C, according to the IPCC's 2007 study. The group also predicted that by 2100, the sea level would rise by 88 cm and there would be a 6-8% increase in rainfall over India. According to the Irrigation Commission of India, a drought is any place where the annual rainfall is less than 75% of what is considered normal. According to relevance, duration, and timing of occurrence, there are generally three types of droughts.

Given that drought is linked to climatic occurrences, factors like rainfall, temperature, and stream flow can serve as reliable predictors of the presence or absence of drought [6]. Then, these indications can be transformed into drought indices that demonstrate the occurrence, extent, severity, and duration of a drought event [7,8]. Both a single input variable and a mixture of hydrological variables can be used to create drought indices [9]. The type of drought being studied and the problem to be addressed determine which hydrological factors should be used in the indicators to produce more certain conclusions. The region of interest and the availability of data also influence the choice of the drought index [10]. There are several drought indices available [11], but the Palmer Drought Severity Index [12], RAI and the SPI, [13] are now the most often used drought indices.

The SPI is multi-scalar because it combines cumulative precipitation deficiencies at different spatiotemporal scales [14]. A key presumption in the calculation of the SPI is that droughts are primarily caused by rainfall variability, whereas other variables, such as temperature, are stationary and, as a result, do not fluctuate over time [15]. The primary advantage of SPI over other indices is that it can identify drought at multiple time periods (1, 3, 6, 12 and 24 months), indicating that diverse types of droughts (meteorological, agricultural, and hydrological) may be tracked. However, according to Tirivarombo and Hughes [16], the quality of a drought index output is only as good as the input data. The classification of the positive and negative severities of rainfall anomalies is done using the RAI, which was created by Rooy [17]. Because it just requires precipitation data, it is regarded as an index of outstanding procedural simplicity [18,19]. Regarding the Keyantash and Dracup [20] stated evaluation criteria for drought indices, the RAI offers a higher degree of transparency and tractability and requires a lower degree of sophistication than the SPI. The goal of RAI, according to Rooy [17], is to make it possible to compare precipitation deviations across regions. Using RAI and SPI, the current study was conducted to evaluate the frequency and intensity of drought in the Harohar-Punpun Basin.

2. MATERIALS AND METHODS

2.1 Study Area and Data Collection

This study is focused on a region in India's Harohar-Punpun Basin that is prone to drought area and the study area map with tributaries are represent in Fig. 1 and description of the Harohar-Punpun Basin is shown in Table 1.

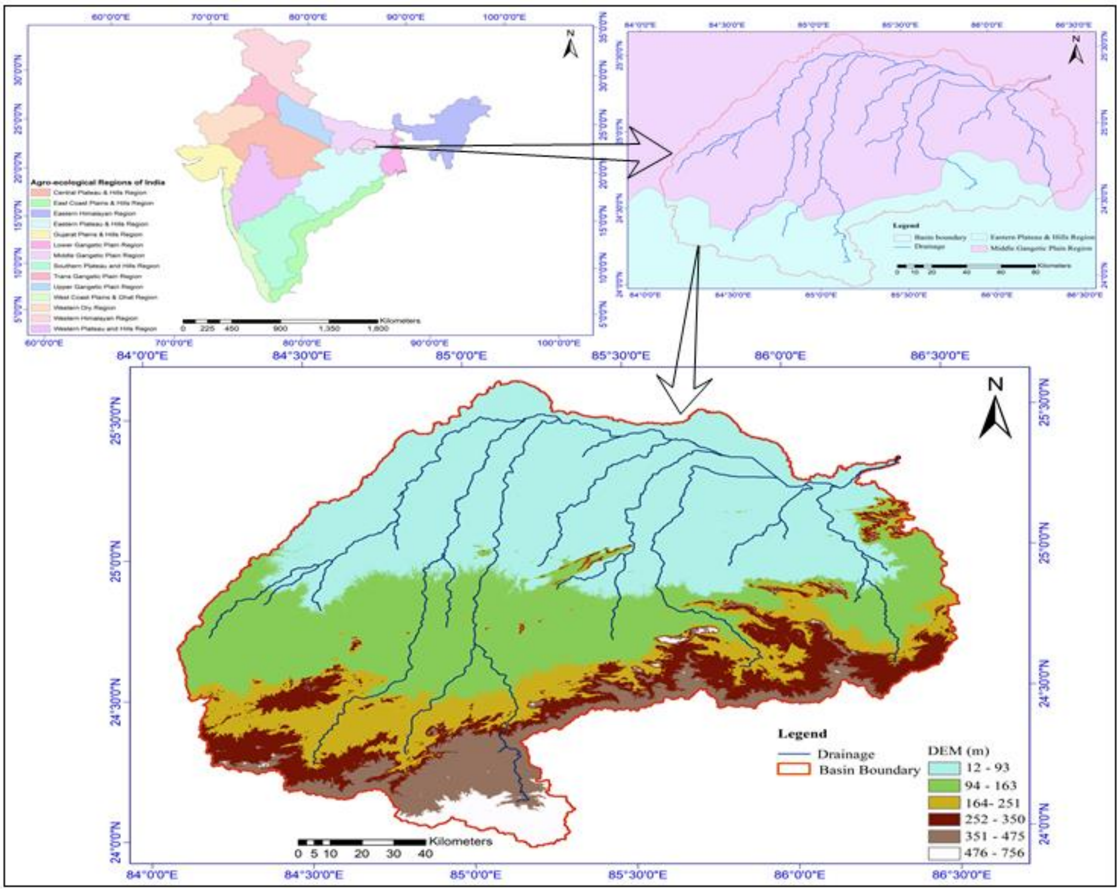


Fig. 1. Study Area

Table 1. Description of the study area

Characteristics	Punpun Basin	Harohar Basin
Basin is situated between	Latitudes-24° 6' N & 25° 35' N Longitude-84° 0' E & 85° 19'E	Latitudes- 24°10' N & 25° 30' N Longitude- 84° 40'E & 86° 8' E
Geographical Area	9025.75 sq.Km	14296.18 sq.Km
Coverage	Patna district, Jehanabad district, Gaya district, Aurangabad district, Nalanda district, Palamu District, and Hazaribagh district.	Patna district, Nawada district, Jehanabad district, Gaya district, Munger District, Nalanda district, Hazaribagh district and Giridih district.
Rainfall (mm)	Average annual rainfall varies from 99 mm near confluence with the Ganga (Patna districts) to 134 cm in the upper most reach (Palamu District).	Average annual rainfall varies from 99 mm in the lower catchment of the river to 126cm in the hills of Hazaribagh district.
Soil Type	Old alluvium grey, grayish-yellow, heavy textured cracking soil	Alluvium –calcareous, light-grey, medium grey to heavy textured soil.

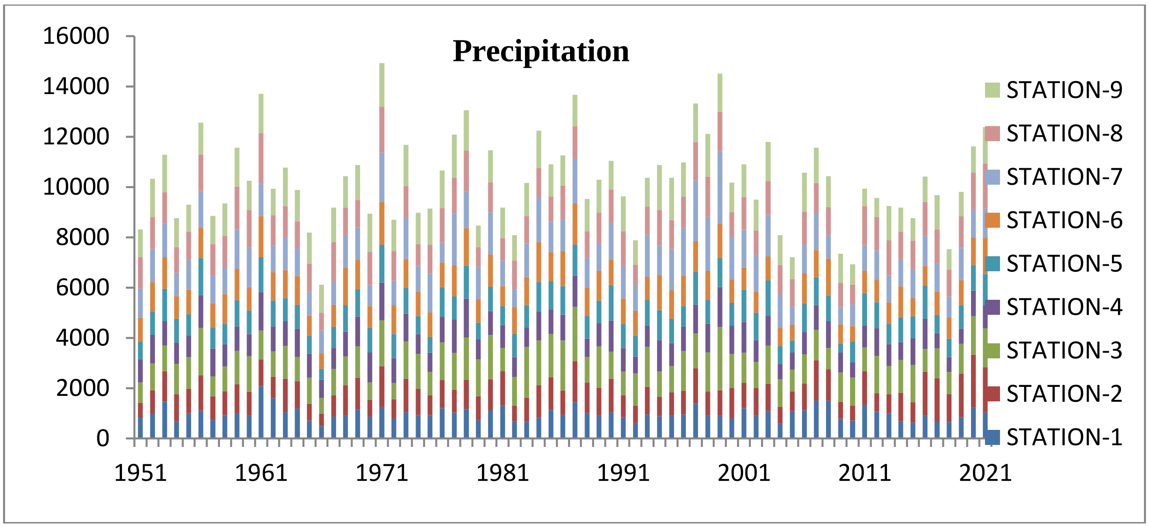


Fig. 2. Yearly precipitation (mm) from 1951 to 2021 for Punpun-Harohar Basin for different Stations

IMD (India Meteorological Department) data of the mean annual and Daily rainfall data from 70 hydrological years (1951 - 2021) for different Metrological Stations are provided in Fig. 2.

2.2 Computation of the Standardized Precipitation Index (SPI)

McKee et al. [13] SPI for the purpose of monitoring drought. Thom (1966) found the gamma distribution to fit climatologically precipitation time series well. The gamma distribution is defined by its frequency or probability density function:

$$G(x) = \frac{1}{\beta^{\alpha}{}_{\tau}{}^{\alpha}} x^{\alpha-1} \; e^{\frac{-x}{b}} \tag{1}$$

Where, α > 0, α is a shape factor. β > 0, β is a scale factor.

$$\Gamma(\alpha) = \int_0^{\infty} y^{\alpha-1} \, e^{-y} \tag{2}$$

Where, Γ (α) is the gamma function.

Computation of the SPI involves fitting a gamma probability density function to a given frequency distribution of precipitation total for a station. From Thom (1966), the maximum likelihood solutions are used to optimally estimate α and β.

$$\acute{\alpha} = \frac{1}{4A}(1 + \sqrt{1 + \frac{4A}{3}}) \tag{3}$$

$$\beta = \frac{x}{\alpha} \quad (4)$$

$$A = \ln x - \frac{\sum \ln(x)}{n} \quad (5)$$

Where, n = number of precipitation observations.

The cumulative probability is given by:

$$G(x) = \frac{1}{\Gamma(\alpha)} \int_0^x t^{\alpha-1} e^{-t} dt \quad (6)$$

The gamma function is undefined for x=0 and a precipitation distribution may contain zeros, the cumulative probability becomes

$$H(x) = q + (1\text{-}q)\, G(x) \quad (7)$$

where q is the probability of a zero. If m is the number of zeros in a precipitation time series, Thom (1966) states that q can be estimated by m/n. The cumulative probability, H(x), is then transformed to the standard normal random variable Z with mean zero and variance of one, which is the value of the SPI. The classification shown in the following table 2 is used to define drought intensities resulting from the SPI computation:

Table 2. Category of Standardized Precipitation Index (SPI) based on range values

SPI Values	Class
>2	Extremely Wet
1.5 to 1.99	Very Wet
1.0 to 1.49	Moderately Wet
-0.99 to 0.99	Near Normal
-1 to –1.49	Moderately Dry
-1.5 to-1.99	Severely Dry
< -2	Extremely Dry

2.3 Computation of the Rainfall Anomaly Index (RAI)

The monthly RAI was calculated for specific years of the historical series aiming to analyze the distribution of rainfall in the years of greatest anomaly. RAI, developed and firstly used by Rooy [17] and adapted by Freitas [18], constitutes the following equations:

$$RAI = 3\left[\frac{N-\dot{N}}{\dot{M}-\dot{N}}\right] \text{ For positive anomalies.} \quad (8)$$

$$RAI = -3\left[\frac{N-\dot{N}}{\dot{x}-\dot{N}}\right] \text{ For negative anomalies} \quad (9)$$

Where:

N = current monthly/yearly rainfall, in order words, of the month/year when RAI will be generated (mm);
$\dot{N}$= monthly/yearly average rainfall of the historical series (mm);
$\dot{M}$= average of the ten highest monthly/yearly precipitations of the historical series (mm);
$\dot{x}$ = average of the ten lowest monthly/ yearly precipitations of the historical series (mm); and positive anomalies have their values above average and negative anomalies have their values below are shown in Table 3.

Table 3. Category of Rainfall Anomaly Index (RAI) based on range values

RAI range	Classification
Above 4	Extremely humid
2 to 4	Very humid
0 to 2	Humid
-2 to 0	Dry
-4 to -2	Very dry
Below -4	Extremely dry

Source: Freitas [18] adapted by Araújo et al. (2009)

2.4 Importance of SPI and RAI as they are important in drought prediction

Using both SPI and RAI allows for cross-verification of drought conditions, where the strengths of one index compensate for the limitations of the other, leading to a more accurate and reliable assessment. For instance, while SPI might indicate a moderate drought over an extended period, RAI can highlight extreme drought conditions that require immediate action [21]. The combination of SPI and RAI offers a balanced approach to drought assessment. SPI's standardization and probabilistic nature provide a broad view of precipitation deficits, while RAI's focus on extremes ensures significant events are not overlooked. This balance is crucial for comprehensive drought monitoring and prediction [22].

3. RESULTS AND DISCUSSION

Where SPI-3 represents the drought index calculated over a time period of 3 month, SPI-6 over a time period of 6 months, and SPI-12 over a time period of 12 months, when the correlation matrices were examined, the strongest relationship was observed among the indices in the same time periods. As the time difference increases (monthly to yearly), the relationship between variables has weakened.

RAI and SPI values are obtained by normalization of rainfall data and give close results in both indices (Fig. 3). However, RAI is simpler, as the calculation procedure does not need to be fitted to any theoretical distribution of data, according to SPI. Furthermore, it is more sensitive in detecting extreme drought and wetlands since it is fluctuating in a wider range.

Table 4. The frequency of Extreme drought by RAI & SPI (3, 6, 12-Month)

SPI-3	**Extreme**	**Frequency (%)**
Station-1	14	1.65
Station-2	13	1.53
Station-3	11	1.30
Station-4	12	1.42
Station-5	15	1.77
Station-6	15	1.77
Station-7	6	0.71
Station-8	18	2.12
Station-9	18	2.12

SPI-6	**Extreme**	**Frequency (%)**
Station-1	22	2.61
Station-2	7	0.83
Station-3	20	2.38
Station-4	26	3.09
Station-5	14	1.66
Station-6	11	1.31
Station-7	21	2.49
Station-8	12	1.43
Station-9	13	1.54

SPI-12	**Extreme**	**Frequency (%)**
Station-1	24	2.89
Station-2	4	0.48
Station-3	17	2.05
Station-4	28	3.37
Station-5	12	1.45
Station-6	4	0.48
Station-7	15	1.81
Station-8	3	0.36
Station-9	9	1.08

RAI	**Extreme**	**Frequency (%)**
Station-1	9	12.68
Station-2	10	14.08
Station-3	11	15.49
Station-4	10	14.08
Station-5	10	14.08
Station-6	12	16.90
Station-7	14	19.72
Station-8	14	19.72
Station-9	13	18.31

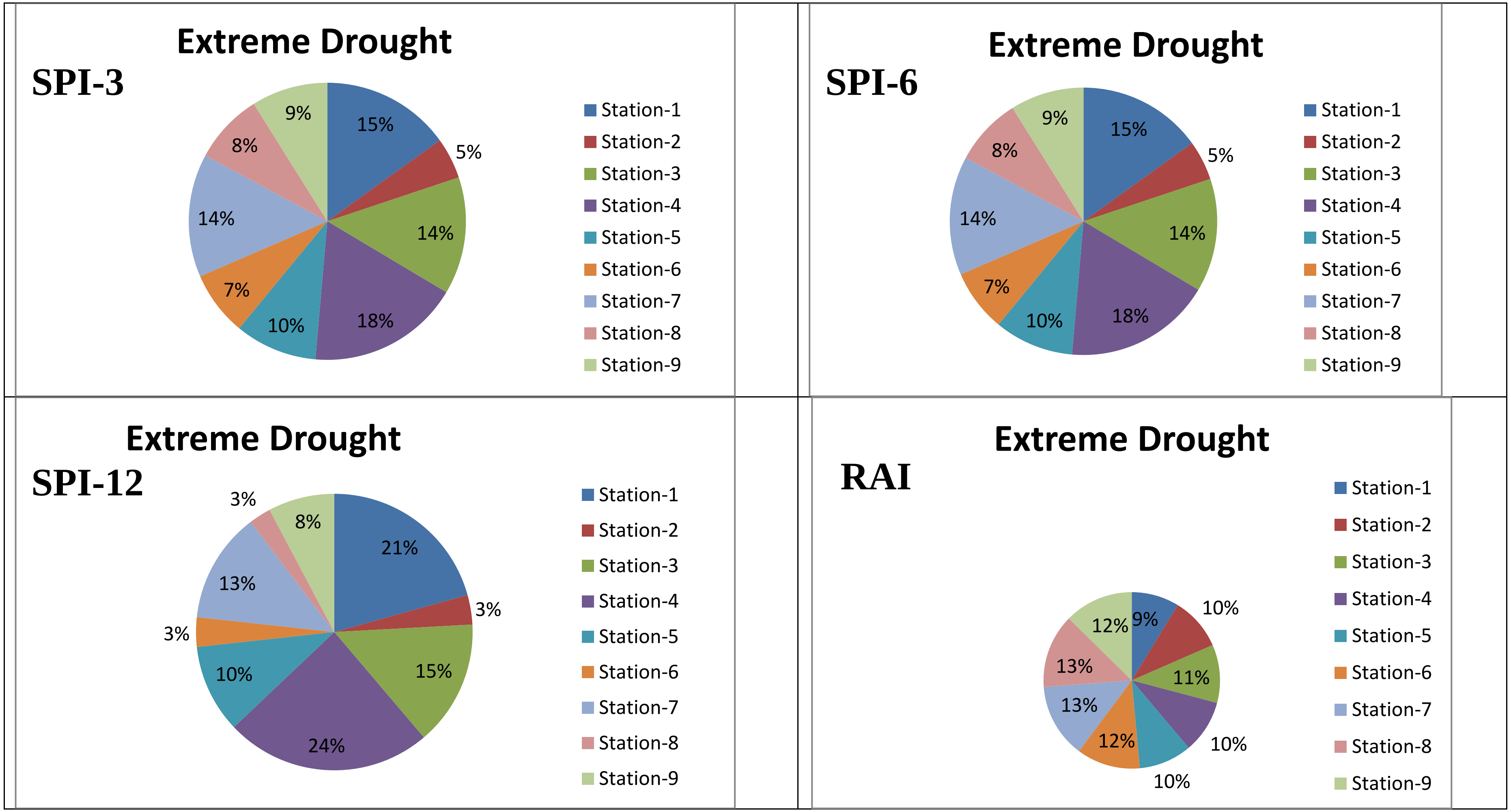
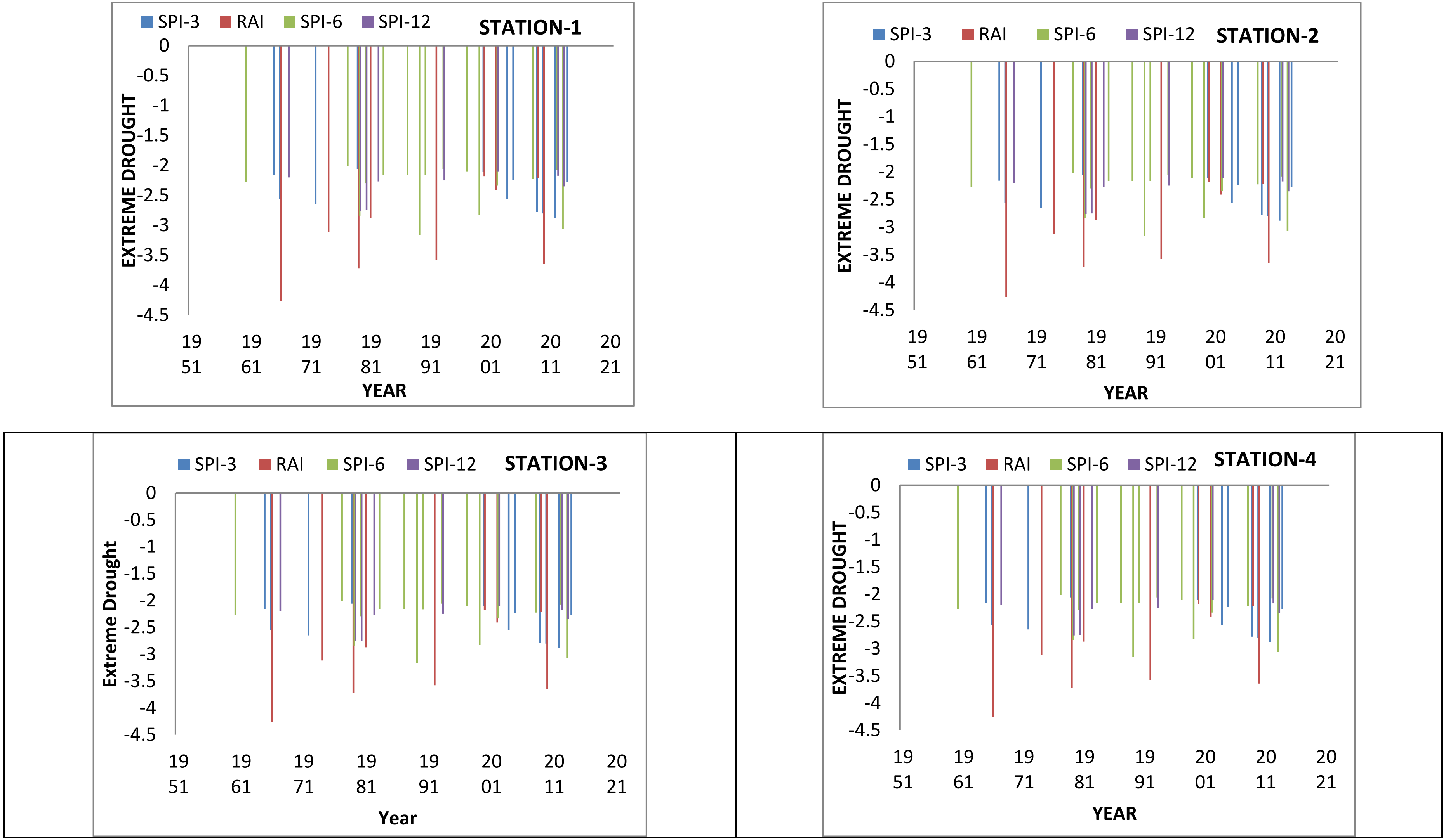
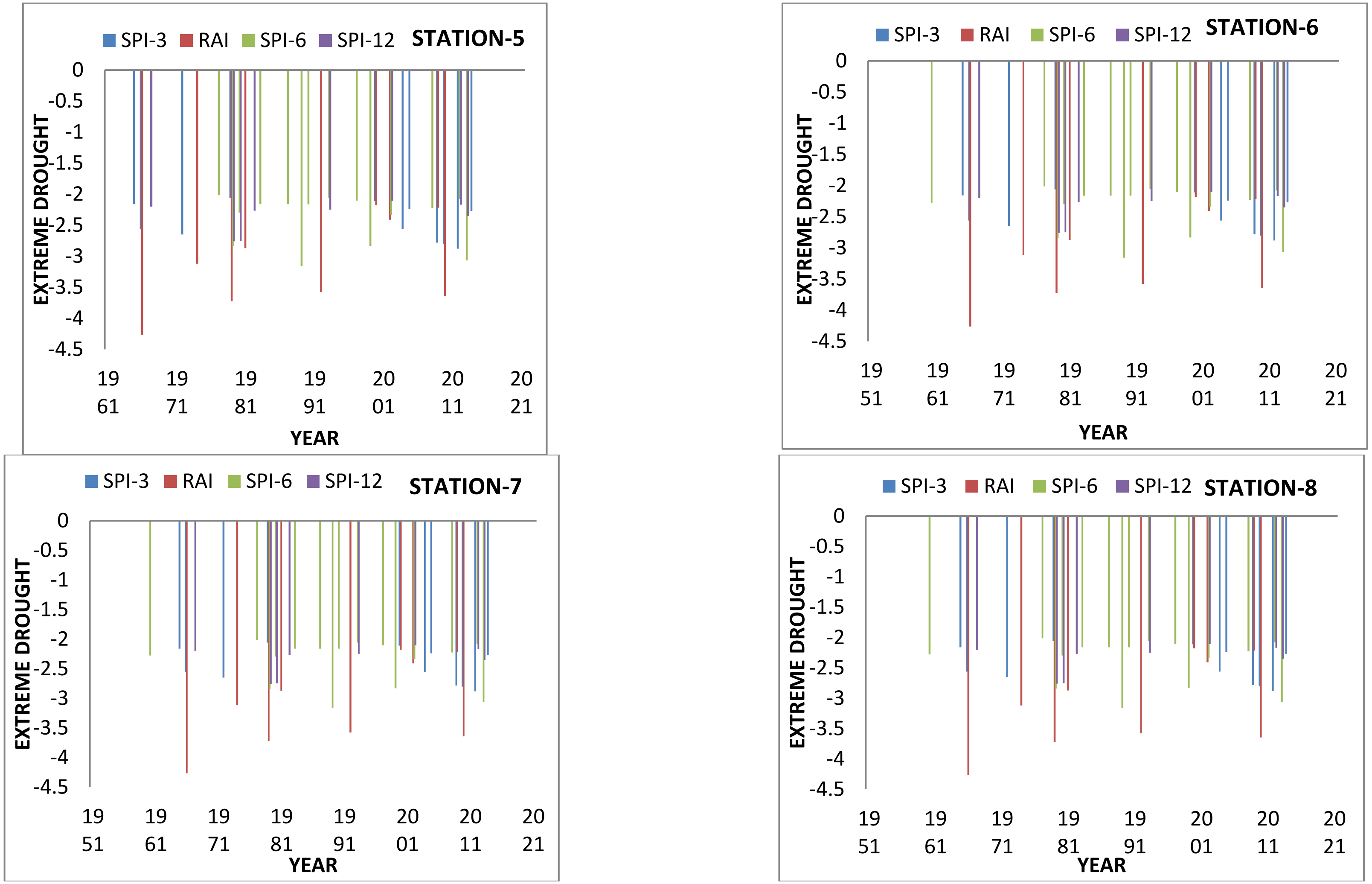


Fig. 3. Extreme Drought events detected by the RAI & SPI (3, 6, 12-Months)


SPI-3
RAI
SPI-6
SPI-12
STATION-1
EXTREME DROUGHT
YEAR
STATION-2
EXTREME DROUGHT
YEAR
STATION-3
Extreme Drought
Year
STATION-4
EXTREME DROUGHT
YEAR


SPI-3 RAI SPI-6 SPI-12 STATION-5
EXTREME DROUGHT
0 -0.5 -1 -1.5 -2 -2.5 -3 -3.5 -4 -4.5
19 61 19 71 19 81 19 91 20 01 20 11 20 21
YEAR
SPI-3 RAI SPI-6 SPI-12 STATION-6
EXTREME DROUGHT
0 -0.5 -1 -1.5 -2 -2.5 -3 -3.5 -4 -4.5
19 51 19 61 19 71 19 81 19 91 20 01 20 11 20 21
YEAR
SPI-3 RAI SPI-6 SPI-12 STATION-7
EXTREME DROUGHT
0 -0.5 -1 -1.5 -2 -2.5 -3 -3.5 -4 -4.5
19 51 19 61 19 71 19 81 19 91 20 01 20 11 20 21
YEAR
SPI-3 RAI SPI-6 SPI-12 STATION-8
EXTREME DROUGHT
0 -0.5 -1 -1.5 -2 -2.5 -3 -3.5 -4 -4.5
19 51 19 61 19 71 19 81 19 91 20 01 20 11 20 21
YEAR

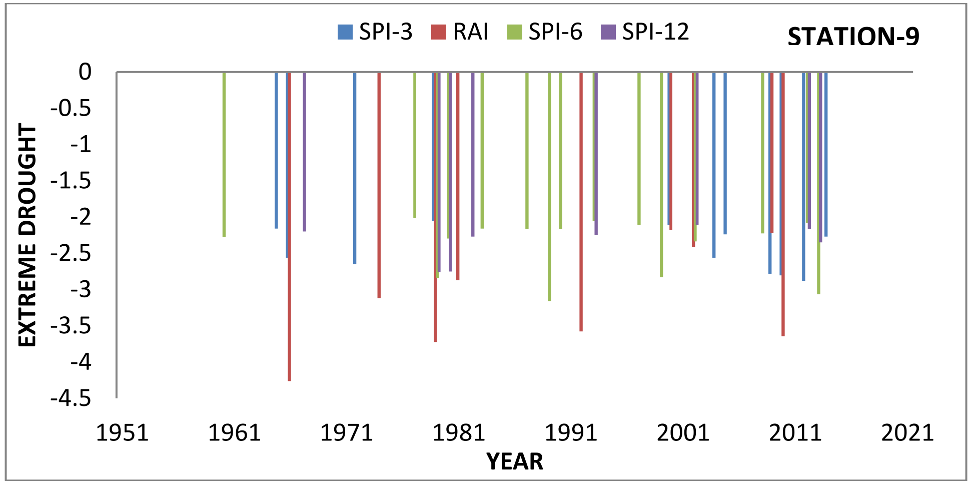


Fig. 4. 3,6,12 month SPI & RAI of extreme drought for Punpun-Harohar basin for Station-1 & Station-9

The frequency of identified extreme drought events using RAI and SPI (3, 6, 12-Month) for various stations is depicted in Fig. 3. In station-8 and station-9, the events were higher compared to the other stations, at 15%, while in station-5 and station-6; it was 12% for SPI-3. In SPI-6, station-1 exhibited a slightly higher value than station-7, with values of 2.69% and 2.49%, respectively. For SPI-12, station-4 and station-1 demonstrated higher values than the others, at 3.37% and 2.89%, respectively, during the period 1951-2021. In terms of RAI, the frequency was higher than that of SPI (3, 6, and 12). This represented a higher value of 19.72% for station-7 and station-8.

3.1 Comparison of SPIs and RAI

At Station-1, the RAI value outperformed SPI. The highest RAI value was -3.19 in 1972, while the lowest was -2.22 in 2009. Likewise, the values for SPI-3, SPI-6, and SPI-12 were -3.19 in 1972, -3.34 in 1979, and -2.89 in 1979, respectively. At Station-2, the RAI value was higher than the others, which were -4.15 in 2011. The values of SPI-3, SPI-6, and SPI-12 were -2.55, -2.63, and -2.50 in 1982, 1966, and 1967. At Station-3, SPI-3, SPI-6, SPI-12, and RAI values were similar but slightly higher for SPI-3, which was -3.78 in 2008. At Station-4, Station-5, Station-6, Station-7, Station-8, and Station-9, the RAI value was greater than that of all stations and SPIs. Which has the most negative anomalies Concentrated in the southern portion of the study area: the values were -5.08, -4.06, -3.79, -4.26, -3.96, and -4.01 in 2009, 1966, 2009, 1966, 1966, and 1957. In 1972, the RAI value was similar to that of 1957. This is under extremely dry category. At Station-3, the values of SPI-3, SPI-6, and SPI-12 were higher than in other stations. These were -3.78, -3.91, and -3.03 in 2008, 2006, and 1967. The entire study area falls under the dry RAI and SPIs category [23].

4. CONCLUSION

The current study aims to identify and assess the frequency of extreme drought in the southern part of the Harohar-Punpun Basin, Bihar. The RAI (Rainfall Anomaly Index) and SPIs (Standardized Precipitation Indices) methods were employed to evaluate extreme drought conditions in the study area. Analysis of rainfall data indicates that 1951 and 2021 experienced the lowest average rainfall, with recorded values of 990 mm and 1340 mm, respectively. Among the rainfall stations, stations 7, 2, and 3 exhibited the highest annual average rainfall, while stations 8, 9, and 6 demonstrated a medium annual average in the study area. The comprehensive investigation highlights the susceptibility of the southern part of the study area to prolonged dry spells. The RAI, serving as a metric for Rainfall Anomaly, facilitates comparisons between SPIs across different regions and allows for the assessment of drought frequency. Consequently, RAI proves to be a valuable tool in understanding the historical rainfall patterns of specific locations. The results demonstrate that the RAI value yielded more accurate outcomes compared to SPIs. This study holds significance in identifying potential drought-prone areas and serves as a valuable resource for planning and implementing mitigation strategies.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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