Assessing Extreme Drought Using the Standardized Precipitation Index (SPI) in the Harohar-Punpun Basin, Bihar, India

Abstract

By definition drought is a long period of deficient rainfall, especially one that badly affects growing or living conditions. Rainfall is believed to be a normal, wet and dry climate condition. It is one of the most important water-associated hazards. It greatly impacts on agricultural, hydrological, economic, environmental and social systems. Understanding these impacts is crucial for drought planning, mitigation, and response. It also helps decision-makers identify and reduce vulnerability to drought. A drought index value is a single number, far more valuable than raw numbers for result-making. The standardized precipitation index (SPI) has several characteristics that are upgrading over other indices, with its simplicity and flexibility.

The standardized precipitation index (SPI) method is used for observing and describing drought based on seventy (70) years of precipitation data from the Harohar-Punpun Basin, Bihar. Finding drought index with 3- month, 6-month, 12-month, time scale basis. Positive SPI values point to normal condition to wet condition and negative values indicate normal condition to dry condition. In this work, we computed years of intense drought between 1951 and 2021. We investigated how the effects of extreme drought varied across nine stations. At SPI-3, station-3 has a high extreme drought value, of -3.78 in 2008 and low extreme drought value of -2.63 in 2011 at station-9. Similar SPI-6 and SPI-12, station-3 has the highest extreme drought, which has found to be -4.20 in 2009, and station-2 has the lowest extreme drought, which was found to be -2.63 in 1966. Station-4 has the highest extreme drought, calculated as -3.39 in 1967, and station-6 has the lowest extreme drought value, which has -2.4 in 2018. Stations 8 and 9 in SPI-3 have a frequency of the same, which are 2.12. In comparison to other stations, they have the highest frequency. Station 4 in SPI-6 and SPI-12 has a high frequency of 3.09 and a low frequency of 0.87, while station 4 in SPI-12 has a high frequency of 3.37 and a low frequency of 0.36.

Key word: Rainfall, Standardized precipitation index , drought Assessment

1. Introduction

The most significant climate hazard that harms both natural and socioeconomic systems is drought, a common occurrence in the climate [1]. Therefore, understanding drought is essential for managing and planning water supplies [2–4] and to implementing strong mitigation strategies, minimize the socioeconomic effects of prolonged drought [5,6]. "Droughts are typically divided into four categories: meteorological, agricultural, hydrological, and socio-economic" [7]. A Lack of precipitation is referred to as a meteorological drought, the first event in the emergence and development of drought conditions [8]. The term "hydrological drought" describes a lack of surface and groundwater resources [9]. Agricultural dryness typically results in decreased soil moisture and decreased crop output [10]. Lastly, socioeconomic drought is linked to the water resources system's failure to meet human demand. [11]. Many indicators have been presented in recent decades to identify and track drought [12]. The primary aspects of drought, such as severity, duration, and extent, are objectively quantified and compared across locations with different meteorological and hydrologic regimes using drought indices [13].

Among the existing indexes, the Standardized Precipitation Index (SPI; [14]) is widely used worldwide for its simplicity, applicability at different locations and time scales [12]. “Furthermore, SPI’s main advantage lies in using of precipitation as the only input to assess the drought. Indeed, it requires only rainfall monthly time series and can be computed for different time scales (e.g., usually 3, 6, 12, 24 and 48 months). For clarity, in this work, we shorten the name of the SPI to include the time scale: for example, SPI3 is the SPI evaluated with a 3-months’ time scale. According to the standard procedure proposed by McKee et al. , monthly cumulated series of observed precipitation values, at any time scale, are fitted with a Gamma distribution, whose parameters are evaluated with the Maximum Likelihood Estimation (MLE) method”. [14]

“Global economic losses due to droughts are estimated to be as high as 600-800 million dollars per year, much greater than those due to other meteorological disasters” [15]. “Therefore, it is necessary to conduct monitoring and assessment globally or in each area to determine drought intensity, magnitude, duration and spatial extent and to provide a basis for fighting drought and drought relief. Therefore, selecting or developing an index to describe drought is necessary. Therefore, drought management in agriculture is a major challenge for Bihar in achieving sustainable agricultural development. To tackle the drought efficiently, it is essential to understand the spatial-temporal pattern of drought evolution in Bihar. Drought assessment plays an important role in the planning and management of water resources. For assessment, some numerical standard is needed so that drought measures can be compared between regions and can be compared with past drought events” [16].

“Drought indices use hydro-meteorological data such as rainfall, stream flow, reservoir storage, soil moisture, groundwater, and water supply indicators either independently or collectively” [17].

“Drought is having certain characteristics, such as they usually take an elliptic profile. Being of slow start, it is difficult to determine the beginning and end of the drought event. The duration may vary from months to years and the core area or epicenter changes over time. The impacts are non-structural and not easy to compute. It is a creeping phenomenon. The impacts of drought are increasing and the effects expand when events continue from one season or year to the next. It does not have a sharp ending. Strong points favoring the use of the SPI are its capacity to be calculated on different time-scales to adapt to the varied response times of typical hydrological variables to precipitation deficits. It allows detecting different drought types that affect different systems and regions. Although the SPI has shown to be useful for drought monitoring and early warning , deficiencies have also been noticed related to its inability to detect drought conditions determined not by a lack of precipitation but by a higher than normal atmospheric evaporative demand”. [18]

Developing States including Bihar and developed states Jharkhand of India that tend to share similar sustainable development challenges, including small but growing populations, limited resources, remoteness, susceptibility to natural disasters, vulnerability to external shocks, excessive dependence on international trade, and fragile environments. Their growth and development is also held back by high communication, energy and transportation costs, irregular international transport volumes, disproportionately expensive public administration and infrastructure due to their small size, and little to no opportunity to create economies of scale.

However, GIS-based long- term drought monitoring and assessment in Bihar and Jharkhand is uncommon. The study's objective is to know Bihar's the spatial and temporal drought pattern using long-term (historical data) data. This study will provide a basis for the projection of future climate extremes over Harohar- Punpun basin under different drought scale. Moreover, the study's finding will provide potential socio–economic implications for policy–makers to design climate change adaptation and mitigation strategies in the region.

2. Study Area and Data Collection

The Punpun-Harohar basin is located in the Bihar and Jharkhand, India. This basin is situated between latitude 24^0 6'N and 25^0 35' N and 24^0 10' N and 25^0 30'N and longitude 84^0 0'E and 85^0 19'E and 84^0 40'E and 86^0 8'E. The total geographical area of the Punpun basin is 9025.75sq.Km and Harohar basin is 14296.18 sq.Km. The Punpun basin cover the Patna, Jehanabad, Gaya, Arungabad, Palamu, Nalanda and Hazaribagh district. The Harohar basin cover the Patna, Nawada, Jehanabad, Gaya, Hazaribagh, Giridih, Munger and Nalanda district. Total 9 sub stations are located in this map. Location map of the study area is shown in Fig.1.

The river Punpun originates from Harihargang block of Palamu District in the Chotanagpur Plateau at the elevation of 442 m. In the head reach it receives the tributaries like Batane, Adari, Madar and Kalan and in the lower reach the river has got two main tributaries known as Morhar and Dardha both running almost parallel to each other and meeting the main stream on the right bank east of Patna-Gaya road. After traversing about 15 Km in the north-east direction the Punpun falls in the river Ganga near Fatuha about 20Km east of Patna.

The river Harohar is the principal tributary of the river Kiul having its sub- tributaries like the Dhadhar, the Sakri, the Kaurihari, the Panchane and the Phalgu. The river Phalgu is the united stream of Mohane and Lilajan, both having their origins in the hills of Hazaribagh district. The river Paimar rises near the village Sichugora in Nawada district and is joined by a branch of river Phalgu and falls into the Dhoa. Dhoa later gets converted into the Harohar.

The Average annual rainfall of the Punpun basin varies from 99cm near confluence with the Ganga (Patna District) to 134cm in the uppermost reach (Palamu District). About 85 to 87 percent of the annual rainfall occurs during the monsoon period from June to September. The maximum value of 24Hours rainfall with 50 years frequency is 32cm which occurs in the upper catchment while other portions it is between 24 to 28cm. In Harohar basin, the average annual rainfall varies from 99cm in the lower catchment of the river to 126cm in the hills of Hazaribagh district .About 85 percent of the annual rainfall occurs Seventy years of precipitation data has been collected from Indian Meteorological Department (IMD) for this study from 1951 to 2021. Variations in the yearly precipitation for seventy years from 1951 to 2021 are shown in Fig. 2.

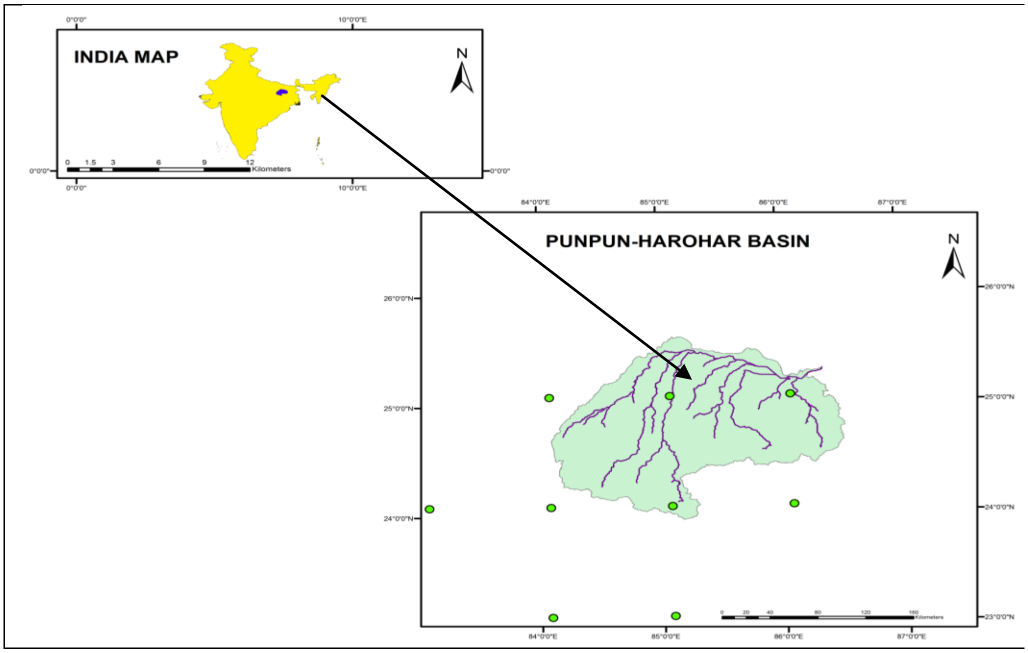

Fig 1: Study Area

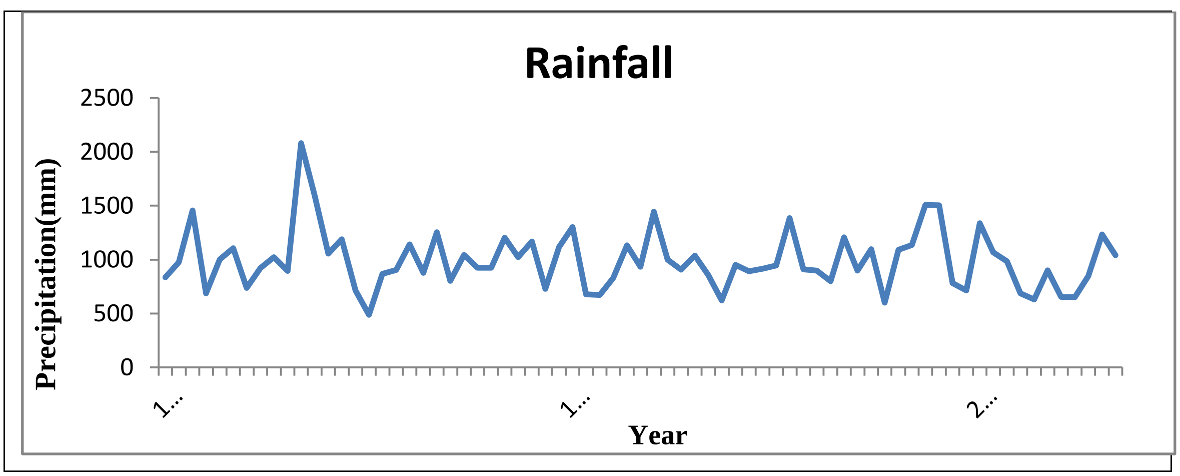

Fig. 2. Yearly precipitation (mm) from 1951 to 2021 for Punpun-Harohar Basin

3. **Computation of the Standardized Precipitation Index (SPI)**

McKee et al. (1993) developed the Standardized Precipitation Index (SPI) to monitor 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:

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

Where, $\alpha > 0$, α is a shape factor. $\beta > 0$, β is a scale factor.

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

Where, $\Gamma(\alpha)$ 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 estimate α and β optimally

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

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

$$A = l_n\, x - \frac{\sum \ln(x)}{n} \qquad (5)$$

Where, n = number of precipitation observations.

The cumulative probability is given by:

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

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

$$H(x) = q + (1-q)\, G(x) \qquad (7)$$

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 is used to define drought intensities resulting from the SPI computation:

Table 1. 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

Table 2. Category of Standardized Precipitation Index (SPI) based on Extreme Draught only for this region

SPI Values	Class
Highly Extreme	<3.5
Moderate Extreme	2.76 to 3.49
Fairly Extreme	2 to 2.75

4. Results and Discussion

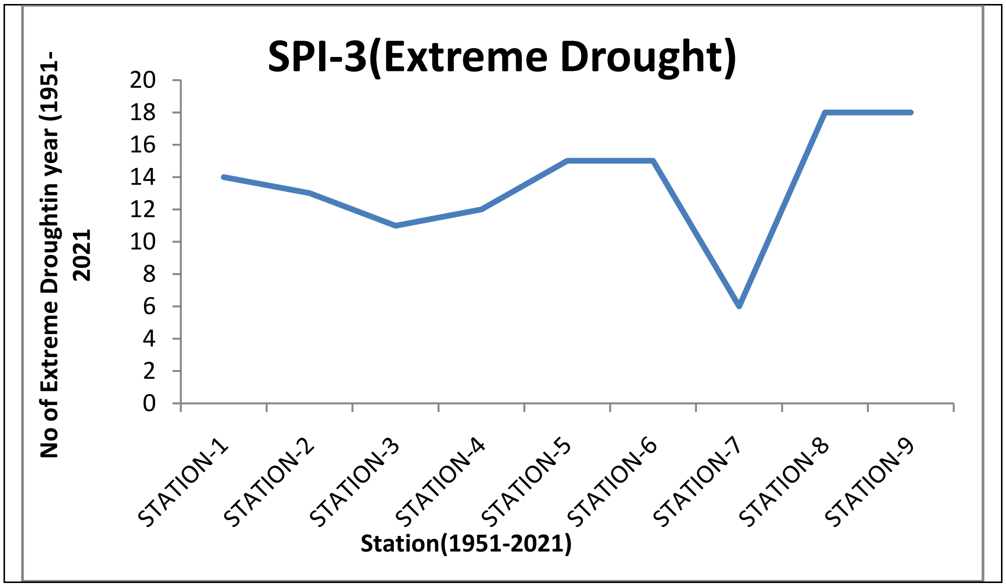

Fig.3 3-month SPI of Extreme Drought for Punpun-Harohar Basin

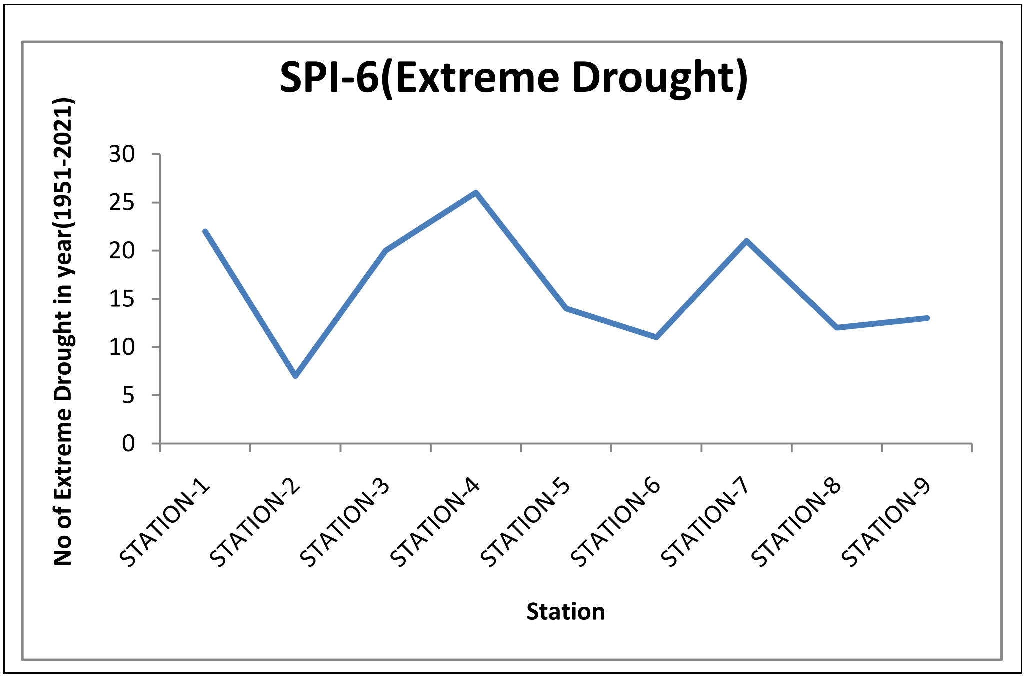

Fig.4 6- month SPI of Extreme Drought for Punpun-Harohar Basin

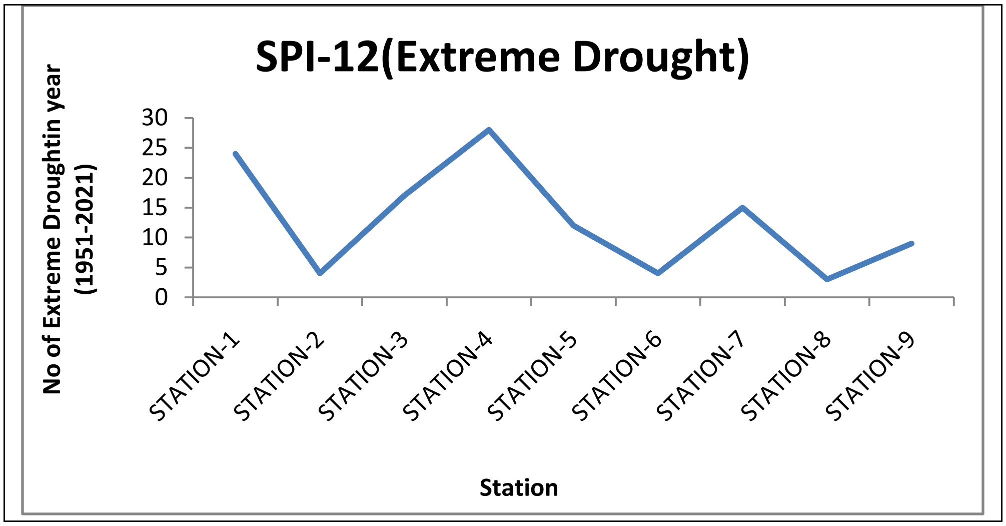

Fig.5 12- month SPI of Extreme Drought for Punpun-Harohar Basin

Table 3. Total number of events of Extreme Drought in Punpun-Harohar Basin

No. of Station	SPI-3	SPI-6	SPI-12
STATION-1	14	22	24
STATION-2	13	7	4
STATION-3	11	20	17
STATION-4	12	26	28
STATION-5	15	14	12
STATION-6	15	11	4
STATION-7	6	21	15
STATION-8	18	12	3
STATION-9	18	13	9

The results for the Punpun-Harohar basin were evaluated, and it found that the results of different SPI-3, SPI-6 and SPI-12 station have quite different results as per their respective categories. These models were calculated using rainfall data over 70-year period at nine stations. The extreme drought events for 9 stations of 3, 6 & 12 month SPI in Table 3 are shown. The value of station 8and 9 in SPI-3 is 18 , which is the highest event value of this month and for 6th and 12th month, the maximum number of SPI has come at the 4th station, whose event value is 26 and 28.

Table 4. Extreme Drought in different Year at SPI-3 and SPI-6

SPI-3				SPI-6			
No. of Station	Year	Month	Extreme Drought	No. of Station	Year	Month	Extreme Drought
1	1972	6	-3.19	1	1989	4	-4.10
2	1972	6	-3.17	2	1966	12	-2.63
3	2008	11	-3.78	3	2009	3	-4.20
4	1988	11	-3.28	4	1999	4	-3.78
5	2008	10	-3.1	5	2009	1	-3.20
6	1966	9	-3.05	6	2001	3	-3.26
7	1982	9	-2.69	7	1995	5	-3.03
8	1966	9	-2.71	8	1982	2	-2.77
9	2011	12	-2.63	9	1972	8	-3.26

Table 5. Extreme Drought in different Year at SPI-12

SPI-12			
No. of Station	Year	Month	Extreme Drought
1	1980	2	-2.92
2	1967	6	-2.99
3	1967	2	-3.18
4	1967	6	-3.39
5	1982	7	-2.53
6	2018	12	-2.4
7	1967	6	-2.99
8	1958	7	-2.86
9	1973	3	-2.44

Table 4 & 5 shows extreme drought in different Year at SPI-3, SPI-6 & SPI-12. Maximum extreme drought was found in 11 months of 1988 in 3-month SPI, whose value is -3.78 at station 3, and the lowest value was -2.63 in 2011 at station 9. Similarly, in 6 and 12 months of maximum SPI were -4.10 and -3.39, found in year 1989 and 1967 at station 1and 2. In SPI-3, SPI-6 and SPI-12, we see that extreme drought has started since 1966. Extreme drought comes once in about ten years or less.

Fig 6 and 7 shows graphical representation of SPI 3, SPI6 and SPI12 of different Extreme Droughts for the Punpun-Harohar Basin for the basis of Table 2. To know more accurately about the result of Extreme Drought, we have divided the Extreme Drought for this area into three parts. According to spi-3, spi-6 & spi-12, station 3 has shown highly extreme drought. This can be seen in the figure6 and 7. Furthermore, moderate drought has come 6th time in SPI-3, SPI-6 and SPI-12. Whose highest value is -3.46.

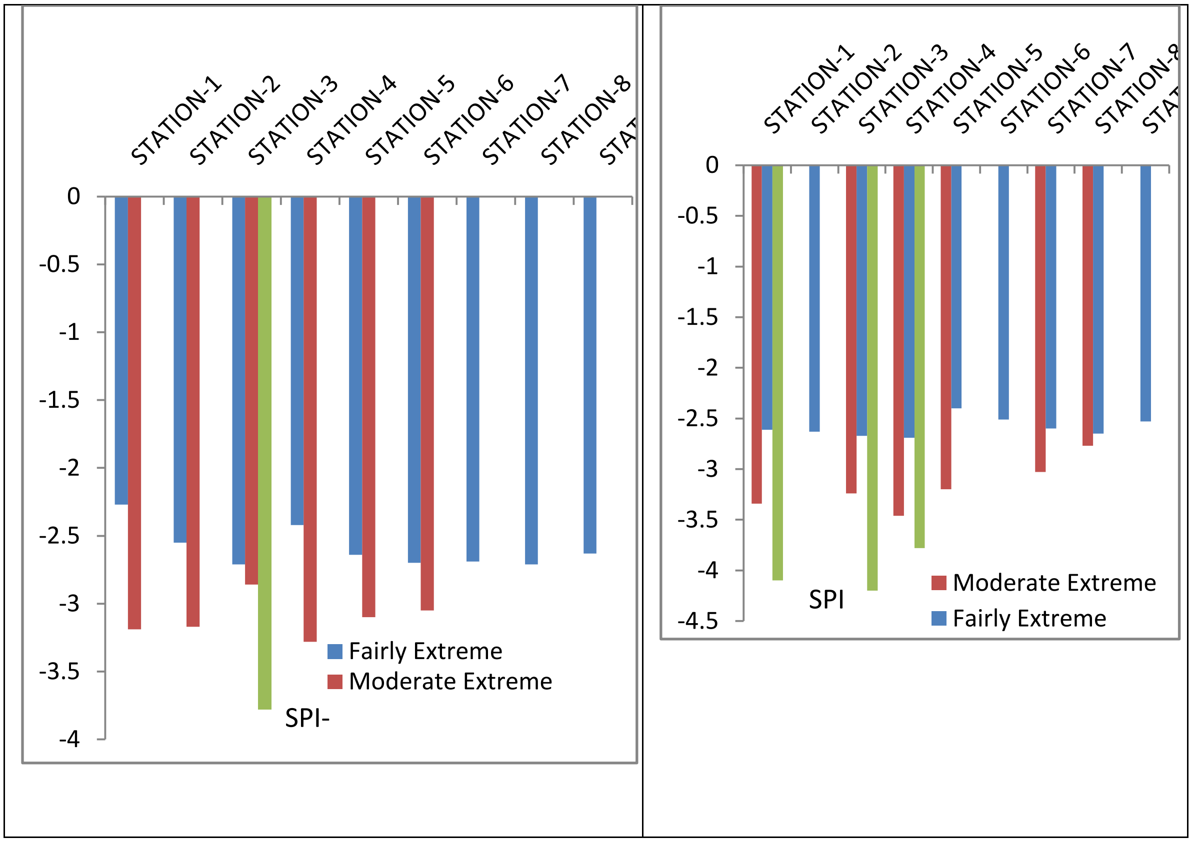

Fig.6 3 & 6- month SPI of different Extreme Drought for Punpun-Harohar Basin

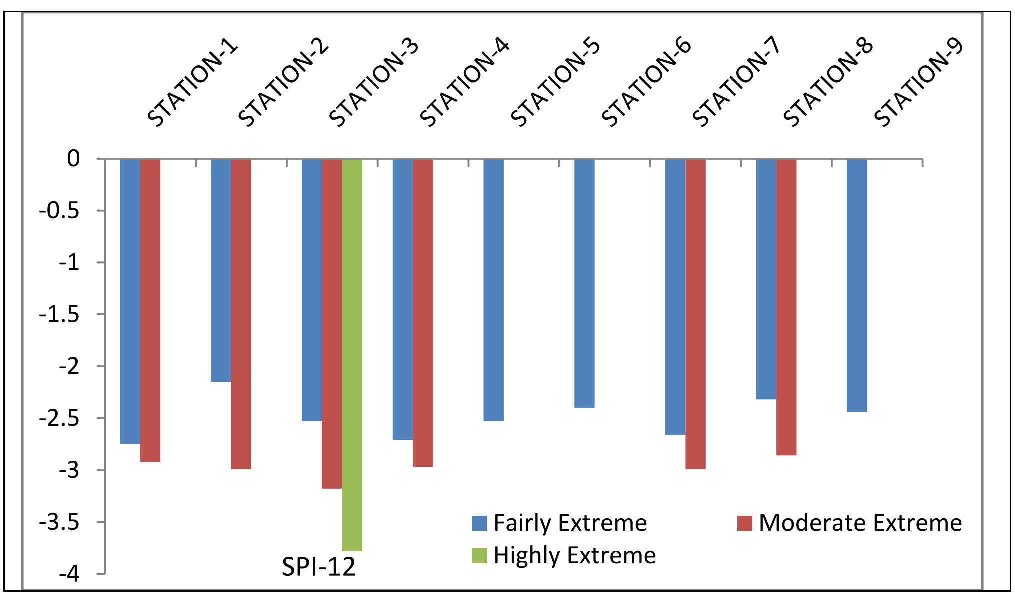

Fig.7 12- month SPI of different Extreme Drought for Punpun-Harohar Basin

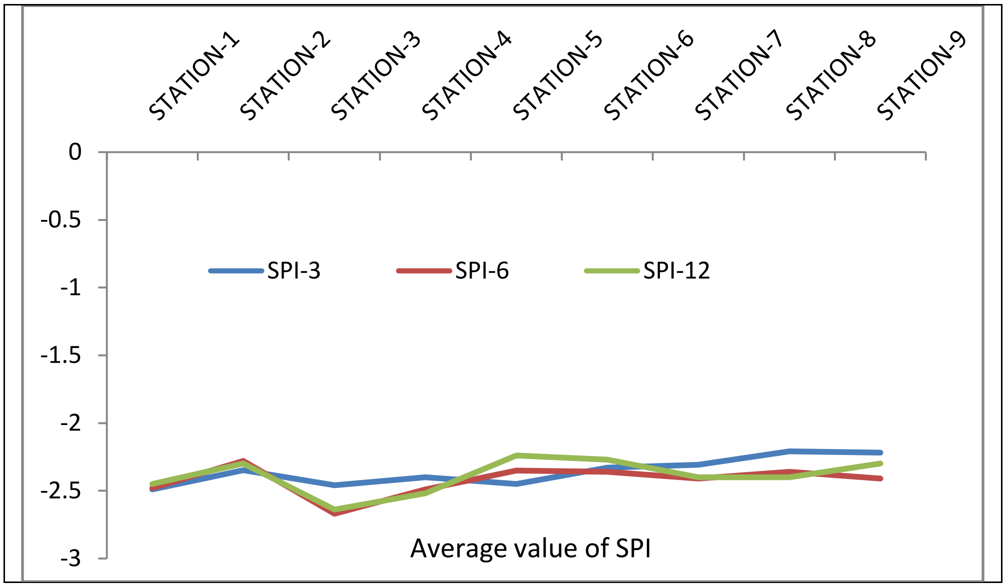

Fig.8 3, 6 &12- month SPI of Extreme Drought for Punpun-Harohar Basin

Table 6. Average Extreme Drought in different Station at SPI-3 and SPI-6

No. of Station	SPI-3	SPI-6	SPI-12
STATION-1	-2.49	-2.48	-2.45
STATION-2	-2.35	-2.28	-2.3
STATION-3	-2.46	-2.67	-2.64
STATION-4	-2.4	-2.49	-2.52
STATION-5	-2.45	-2.35	-2.24
STATION-6	-2.33	-2.36	-2.27
STATION-7	-2.31	-2.41	-2.4
STATION-8	-2.21	-2.36	-2.4
STATION-9	-2.22	-2.41	-2.3

5. Conclusion

As a result, the primary goal of this study was to evaluate droughts identified in the Punpun-Harohar basin's historical rainfall data using the Standardized Precipitation Index criterion. The analysis of temporal patterns in drought produced many intriguing results about the variability in the incidence of drought in the area. The rainfall data in this basin showed an increasing trend, indicating that the areas under examination are drought-prone. In order to evaluate drought characteristics like frequency and severity, it was found that SPI is a useful method. Due to the fact that it employs just precipitation data and provides reliable results, the SPI technique performs best without the using other environmental parameters such as minimum and maximum temperatures, humidity, potential evapotranspiration (ETo), and sun hours. Results from the SPI-3, SPI-6, and SPI-12 methods are comparable to those from other extreme drought situations.

Because it is straightforward and efficient, this approach is preferable for agricultural applications.

Reference

1.Baronetti, A.; González-Hidalgo, J.C.; Vicente-Serrano, S.M.; Acquaotta, F.; Fratianni, S. A weekly spatio-temporal distribution of drought events over the Po Plain (North Italy) in the last five decades. Int. J. Climatol. **2020**, 40, 4463–4476.

2. Cancelliere, A.; Salas, J.D. Drought length properties for periodic-stochastic hydrologic data. Water Resour. Res. **2004**, 40, 1–13.

3.Kreibich, H.; Van Loon, A.F.; Schröter, K.; Ward, P.J.; Mazzoleni, M.; Sairam, N.; Abeshu, G.W.; Agafonova, S.; AghaKouchak, A.; Aksoy, H.; et al. The challenge of unprecedented floods and droughts in risk management. Nature **2022**, 608, 80–86.

4.Burgan, H.I.; Aksoy, H. Daily flow duration curve model for ungauged intermittent subbasins of gauged rivers. J. Hydrol. **2022**,604, 127249.

5. Lloyd-Hughes, B.; Saunders, M.A. A drought climatology for Europe. Int. J. Climatol. **2002**, 22, 1571–1592.

6. Garcia, M.; Ridolfi, E.; Di Baldassarre, G. The interplay between reservoir storage and operating rules under evolving conditions. J. Hydrol. **2020**, 590, 125270.

7. American Meteorological Society (AMS). Statement on meteorological drought. Bull. Am. Meteorol. Soc. **2004**, 85, 771–773.

8. Kumar, M.N.; Murthy, C.S.; Sesha Sai, M.V.R.; Roy, P.S. On the use of Standardized Precipitation Index (SPI) for drought intensity assessment. Meteorol. Appl. **2009**, 16, 381–389.

9. Van Loon, A.F. Hydrological drought explained. WIREs Water **2015**, 2, 359–392.

10. Liu, X.; Zhu, X.; Pan, Y.; Li, S.; Liu, Y.; Ma, Y. Agricultural drought monitoring: Progress, challenges, and prospects. J. Geogr. Sci. **2016**, 26, 750–767.

11. Zhao, M.; Huang, S.; Huang, Q.; Wang, H.; Leng, G.; Xie, Y. Assessing socio-economic drought evolution characteristics and their possible meteorological driving force Assessing socio-economic drought evolution characteristics and their possible meteorological driving force. Geomat. Nat. Hazards Risk **2019**, 10, 1084–1101.

12.Mishra, A.K.; Singh, V.P. A review of drought concepts. J. Hydrol. **2010**, 391, 202–216.

13. Stagge, J.H.; Tallaksen, L.M.; Gudmundsson, L.; Van Loon, A.F.; Stahl, K. Candidate Distributions for Climatological Drought Indices (SPI and SPEI). Int. J. Climatol. **2015**, 35, 4027–4040.

14. McKee, T.B.; Doesken, N.J.; Kleist, J. The Relationship of Drought Frequency and Duration to Time Scales. In Proceedings of the 8th Conference on Applied Climatology, Anaheim, CA, USA, 17–22 January 1993; Volume 17, pp. 179–183.

15. Wilhite, D. A., 2000. Drought as a natural hazard: Concepts and definitions. Drought A Global Assessment 1, 3-18.

16. Heim Jr, R. R. (2002). A review of twentieth-century drought indices used in the United States. Bulletin of the American Meteorological Society, 83(8), 1149-1166.

17. World Meteorological Organization. Standardized Precipitation Index User Guide (M. Svoboda, M.Hayes and D. Wood). (2012) (WMO-No. 1090), Geneva.

18. Hayes, M., Wilhite, D.A., Svoboda, M. and Vanyarkho, O., (1999): Monitoring the 1996 drought using the Standardized Precipitation Index. Bulletin of the American Meteorological Society 80: 429-438.