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Century of Rainfall Dynamics and Drought in Bihar: Patterns, Trends, and Climatic Variability (1901-2021)

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Abstract

Variations in precipitation patterns significantly impact the quality of life, particularly in regions reliant on rainfed agriculture like Bihar, India. Over the past century, global greenhouse gas emissions have caused climate warming and altered hydro-meteorological conditions. These changes have resulted in episodic droughts, floods, increased rainfall variability, and intensified extreme weather events. In Bihar, such variability poses serious risks to the hydrological cycle, especially affecting the reliability of monsoonal rainfall, which is crucial for agriculture. This study examines Bihar's annual and seasonal rainfall distribution, revealing a fluctuating but generally decreasing trend in annual rainfall, particularly in East Bihar. The study finds a significant decline during monsoonal rainfall in Bihar. Dry spells during winter and post-monsoon in Central Bihar have increased, thus affecting soil moisture levels and groundwater recharge. The analysis of the Standardized Precipitation Index (SPI) indicates that occurrences of mild droughts are becoming more frequent in western districts. Effective water management strategies like rainwater harvesting and improved irrigation systems are crucial for enhancing agricultural resilience. Investing in climate-resilient agricultural practices, including drought-resistant crop varieties and improved weather forecasting, will further enhance the state's ability to cope with precipitation variability.

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Keywords

Extreme Weather Events; Hydrological Cycle; Monsoonal Rainfall; Precipitation Variability; Standardized Precipitation Index.

Introduction

Over the last century, global warming—primarily driven by human activities—has disrupted surface moisture levels and altered atmospheric processes, leading to significant shifts in rainfall patterns. These disturbances in the earth-atmosphere energy balance have intensified extreme weather events, causing episodic droughts, floods, and greater

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rainfall variability. In India, such fluctuations in annual rainfall have had far-reaching consequences for the economy, hydrology, and agriculture, particularly in multi-hazard-prone regions. A notable trend is the increasing frequency of heavy rainfall events,[1] while moderate rainfall occurrences are declining whereas regions such as south Bihar experience more frequent and prolonged dry spells.[2,3] Recent studies also indicate a rise in extreme rainfall events, particularly in parts of northwest India.[4]

Bihar, a predominantly rainfed agricultural state, is particularly vulnerable to these changes. The shifting rainfall patterns have disrupted the hydrological cycle, affecting the reliability of monsoonal precipitation. Extensive research on Bihar's rainfall distribution reveals significant variability, with a declining trend in annual rainfall,[5] especially in East Bihar. Seasonal analyses further indicate a reduction in monsoonal rainfall,[6] while summer and post-monsoon precipitation patterns exhibit considerable fluctuations. This variability has profound socio-economic implications, particularly in drought-prone districts, where agricultural productivity is highly sensitive to erratic rainfall.[7] Studies also highlight an increase in extreme rainfall intensity, leading to localized flooding in both rural and urban areas. Notably, spatial variability in rainfall is more pronounced in central and north Bihar,[8] exacerbating flood risks in these regions.

The dual challenge of floods and droughts in Bihar is evident through research on extreme rainfall events and drought indices. Studies indicate a rising trend in extreme rainfall in northern Bihar, leading to recurrent flood conditions in some areas,[9] while others experience droughts due to erratic monsoons. Analytical tools such as the Standardized Precipitation Index (SPI) and the Palmer Drought Severity Index (PDSI) underscore the growing threats to Bihar's agriculture and water resources.[10] Additionally, research examining the link between changing rainfall patterns and crop yields[11] confirms that variations in monsoonal rainfall significantly impact staple crops like rice and wheat. In South Bihar, irregular rainfall has worsened water scarcity, further heightening agricultural risks.[12] Moreover, fluctuating precipitation patterns have reduced groundwater availability,[13] which is crucial for sustaining agriculture during dry spells.

Addressing these climatic challenges is critical for Bihar's future. The increasing unpredictability of rainfall continues to strain agriculture, water resources, and livelihoods. Effective strategies such as sustainable water resource management and climate-resilient agricultural practices are imperative to mitigate risks and ensure long-term economic and environmental stability in the state.

Objectives

- To study the seasonal and annual rainfall distribution and trends in Bihar
- To understand the variability of rainfall and assess drought occurrences.

Materials and Methods

This section discusses the study area, data sources, and methodology adopted for understanding rainfall behaviour and drought assessment in Bihar for the period 1901-2021.

Study Area

Bihar is a landlocked state in eastern India, situated between latitudes 24°17'6" N to 27°30'93" N and longitudes 83°19'17" E to 88°17'47" E, with an average elevation of 150 meters. It borders Nepal to the north, and the Indian states of Uttar Pradesh, Jharkhand, and West Bengal to the west, south, and east. Bihar roughly covers 94.16 thousand square kilometres and is administered into 38 districts. The climate varies greatly, with summer temperatures reaching 43°C and winter temperatures dropping to 5°C. The state gets around 1200 mm of rain annually, mostly during the monsoon season, and is nourished by perennial rivers like the Ganga, Gandak, Ghaghara, Baghmati, and Kosi.

For this study, based on Koppen's climate classification region is divided into 2 major types: (a) Subtropical monsoon (Cwa) and (b) Tropical Savanna (Aw) (Figure 1).

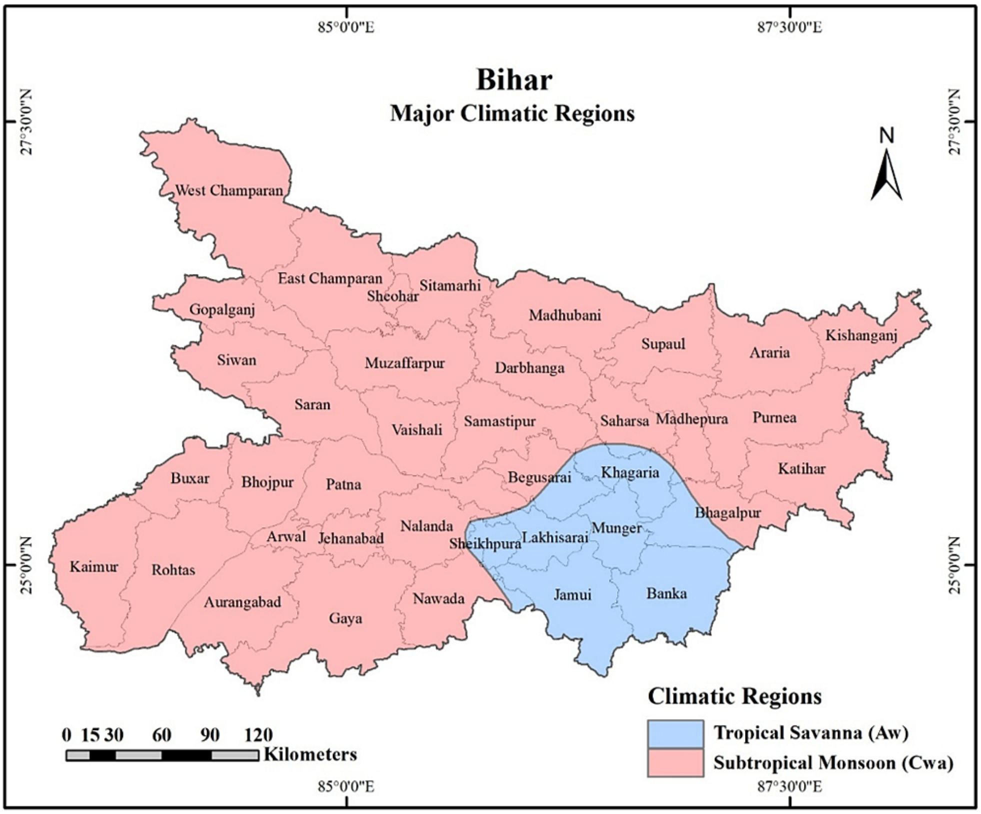


Fig. 1: Study Area (Source: India Meteorological Department)

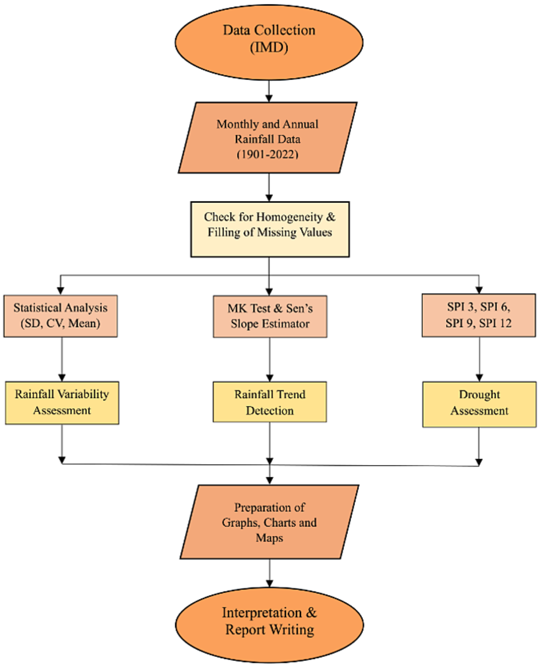


Fig.1.1: Research Methodology

Data Collection and Methodology

The study utilizes long-term monthly rainfall data (1901–2021) at the district level obtained from the India Meteorological Department (IMD) to calculate annual and seasonal precipitation. Missing data were filled using interpolation and mean values from previous years. Rainfall variability was analyzed using Standard Deviation, Range, and the coefficient of variation (CV) for meteorological stations. Trend analysis employed the Mann–Kendall test[14] and Sen's slope estimator[15] at a 95% confidence level. The MK test[14] identifies trends, while Theil and Sen's slope estimator[16,15] measures trend magnitude.

For drought analysis, the Standardized Precipitation Index (SPI) has been calculated for the time interval of 3, 6, 9, and 12 months for each year from 1901 to 2022. It is the most often-used indicator in the world for detecting and describing meteorological droughts.[17] The value of SPI ranges between -2 to +2 (Table 1) where the negative value indicates drought-like conditions, and the positive value indicates wet conditions.[18] Mapping of spatial patterns of rainfall variability and trends have been done in ArcGIS Pro environment.

Table 1: Drought Analysis Index

S. No	Drought Intensity Class	SPI Range
1	Extremely Wet	SPI ≥ 2.0
2	Severely Wet	1.5≤ SPI <2.0
3	Moderately Wet	1.0 ≤ SPI <1.5
4	Near Normal	-1 ≤SPI < 1.0
5	Moderately Dry	-1.5 ≤ SPI < -1.0
6	Severely Dry	-2.0 ≤ SPI < -1.5
7	Extremely Dry	SPI < -2.0

Results

For the present study, rigorous statistical analysis was done at the district level to understand the distribution, trend, and variability of annual and seasonal rainfall.

Spatial Distribution of Annual and Seasonal Rainfall

Table 2 presents the seasonal and annual rainfall data (in mm) for Bihar from 1901 to 2021. Figure 2a highlights the significant variation in annual rainfall distribution, showing a clear decreasing trend from northeast to southwest across the state. Northeastern districts like Kishanganj, Araria, and Purnia receive the highest rainfall (above 1500 mm) due to their proximity to the Himalayas and the Bay of Bengal. Nearby districts such as Supaul, Saharsa, Katihar, and West Champaran receive rainfall between 1300–1500 mm, while central regions like Muzaffarpur and Samastipur experience moderate rainfall. Southwestern districts, including Gaya and Buxar, receive the least, with Buxar recording the lowest annual rainfall at 967.23 mm. Seasonal rainfall variations are highly contrasting. Winter rainfall (Fig. 2b) is generally lower, ranging from 16.45 mm in Saharsa to 37.10 mm in Rohtas, with central and southern regions receiving more rain. Summer rainfall (Fig. 2c) varies from 27.05 mm in Kaimur to 235.52 mm in Kishanganj, with the northeastern region experiencing greater rainfall. The monsoon season accounts for about 80% of annual rainfall, with the northeastern districts receiving the highest rainfall (e.g., Kishanganj: 1801.56 mm). Post-monsoon rainfall (Fig. 2e) also contributes heavy rainfall in northeastern districts like Kishanganj, while southwestern Bihar (e.g., Gaya, Jahanabad, Kaimur, Arwal) remains relatively dry. Region-wise, the subtropical monsoon climate (Cwa) consistently records higher rainfall across all seasons, particularly during the summer and monsoon months, which are crucial for agriculture. In contrast, the tropical savanna climate (Aw) faces challenges due to lower annual and seasonal rainfall receipt.

Table 2: Rainfall Data (1901-2021)

District	Annual	Winter (Jan-Feb)	Summer (Mar-May)	Monsoon (June-Sep)	Post Monsoon (Oct-Dec)
Tropical Savanna Climate (Aw)					
Banka	1124.42	28.89	83.46	918.20	93.87
Begusarai	1135.44	26.28	75.19	960.49	73.48
Bhagalpur	1180.78	26.95	102.86	961.41	89.56
Jamui	1135.31	30.29	70.36	950.30	84.36
Khagaria	1152.64	24.06	79.26	976.13	73.20
Lakhisarai	1087.53	23.48	66.47	922.34	75.25
Munger	1167.00	25.57	76.62	979.28	85.54
Sheikhpura	1016.07	26.69	54.47	871.86	63.05
Subtropical Monsoon Climate (Cwa)					
Araria	1632.33	20.62	178.95	1346.49	86.28
Arwal	968.67	30.89	30.07	854.39	53.32

Aurangabad	1082.67	35.69	33.44	954.39	59.14
Bhojpur	1006.46	28.53	34.86	885.04	58.03
Buxar	967.23	28.28	31.02	849.15	58.79
Darbhanga	1145.20	21.88	94.39	959.91	69.02
East Champaran	1274.90	26.90	90.90	1087.46	69.64
Gaya	1053.17	33.98	39.97	915.96	63.26
Gopalganj	1122.63	25.18	60.03	973.60	63.82
Jahanabad	994.48	31.62	41.67	869.31	51.88
Kaimur	1038.59	33.03	27.05	926.48	52.03
Katihar	1330.85	20.47	132.30	1081.03	97.04
Kishanganj	2162.00	21.16	235.52	1801.56	103.77
Madhepura	1294.77	19.98	118.94	1072.62	83.24
Madhubani	1215.29	19.21	109.11	1018.58	68.39
Muzaffarpur	1156.53	25.81	77.91	983.48	69.32
Nalanda	983.80	27.38	44.42	854.22	57.78
Nawada	1010.77	30.75	44.98	863.60	71.43
Patna	992.58	27.37	48.49	856.63	60.10
Purnia	1537.04	22.49	162.94	1248.82	102.80
Rohtas	1065.32	37.10	35.99	934.92	57.31
Saharsa	1316.59	16.45	134.11	1095.24	70.79
Samastipur	1177.19	27.17	77.49	1000.61	71.93
Saran	1068.61	25.76	52.94	926.28	63.63
Sheohar	1270.04	26.46	93.24	1089.14	61.21
Sitamarhi	1221.52	23.61	103.54	1031.08	63.29
Siwan	1073.69	27.19	50.72	931.65	64.13
Supaul	1318.56	22.25	131.94	1083.81	80.56
Vaishali	1023.12	22.93	54.55	886.50	59.14
West Champaran	1464.29	29.46	111.06	1252.10	71.67

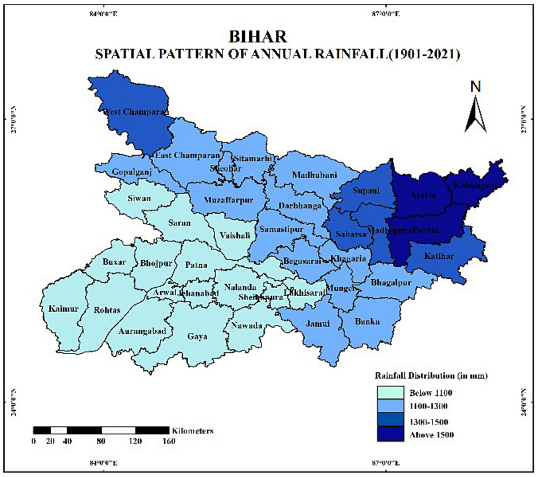


Fig. 2a

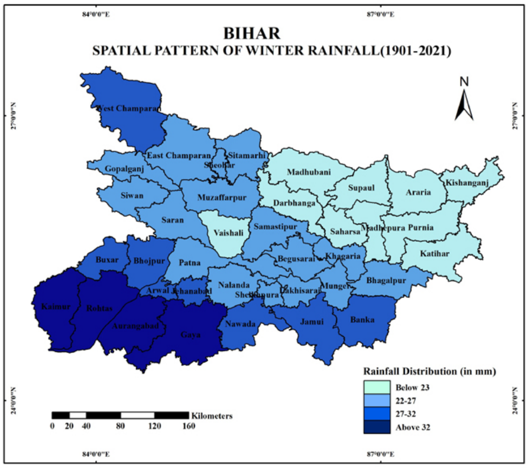


Fig. 2b

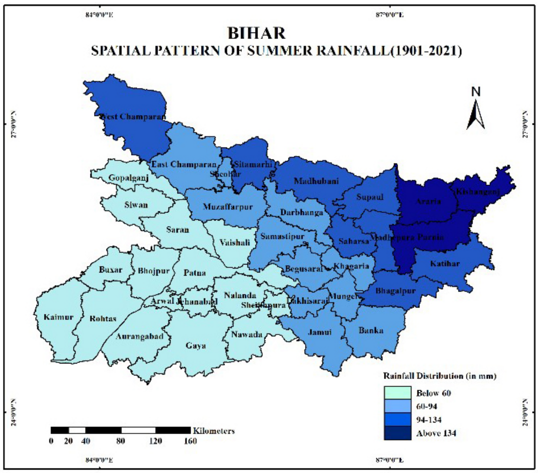


Fig. 2c

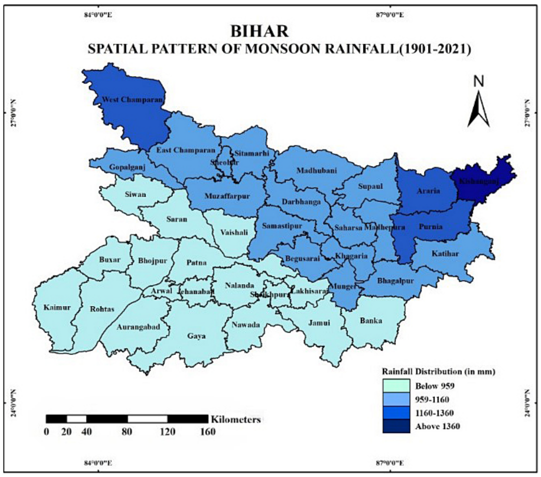


Fig. 2d

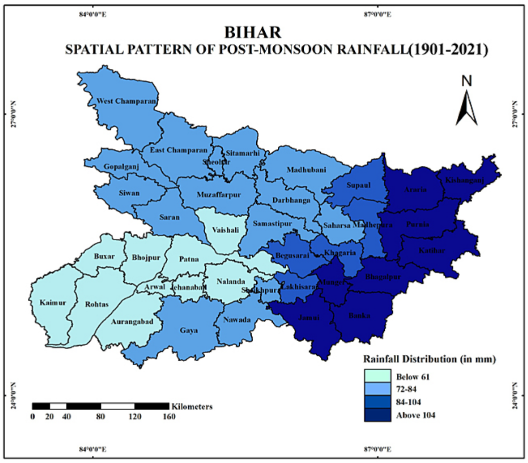


Fig. 2e

Analysis of Annual and Seasonal Rainfall Variability

An analysis of rainfall variability across districts in Bihar reveals distinct patterns of seasonal stability and variability, reflecting the region's diverse climate (Table 3). In the Tropical Savanna region (Aw), districts like Banka (SD: 251.92) and Jamui (SD: 256.24) exhibit moderately high annual standard deviation (SD) values, indicating general stability in rainfall distribution. Monsoon season variability is comparatively low, with Bhagalpur recording an SD of 229.67 and Jamui at 225.82, suggesting a consistent water supply for *Kharif* crops. However, post-monsoon and winter rainfall show higher variability. For instance, Sheikhpura's post-monsoon SD of 81.52 indicates significant fluctuations that could affect soil moisture and Rabi crop irrigation. Winter variability is notable, with Jamui reporting an SD of 32.29 and a coefficient of variation (CV) of 106.58, reflecting unpredictability. Summer SD values are generally lower than those in the monsoon season, with Banka at 29.08 and Jamui at 32.29 (Figure 3a-3e). A study observed that districts in the Tropical Savanna region exhibited relatively stable rainfall patterns during the monsoon season, while those in the Subtropical Monsoon region (Cwa) experienced higher variability, particularly in districts like Kishanganj (Table 3) and Purnia, which aligns with these findings.[19]

Annual rainfall variability is more pronounced in the Subtropical Monsoon region (Cwa), encompassing districts like Kishanganj, Araria, and Purnia. Kishanganj's exceptionally high annual SD of 468.15

and CV of 21.65 indicate substantial annual rainfall with significant variability (Table 3). Monsoon season patterns further emphasize this, as Kishanganj's monsoon SD reaches 438.92, the highest in the state. High SD values also appear in Araria (305.02) and Purnia (330.77), raising flood risk and potential impacts on food security. The winter months show high SD values in districts like Buxar and Arwal, with CVs exceeding 100%, highlighting irregular and unpredictable rainfall (Figure 3a-3e). Summer rainfall displays significant inter-annual fluctuations, as observed in Supaul (SD: 339.48) and Sitamarhi (SD: 311.93).

Table 3: Annual and Seasonal Rainfall Variability (1901-2021)

District	Annual		Winter		Summer		Monsoon		Post-monsoon	
	SD	CV	SD	CV	SD	CV	SD	CV	SD	CV
Tropical Savanna Climate (Aw)										
Banka	251.92	22.40	29.08	100.65	54.15	64.88	213.28	23.23	90.74	100.01
Begusarai	287.37	25.31	24.77	94.24	54.46	72.43	261.07	27.18	74.78	103.58
Bhagalpur	270.76	22.93	25.39	94.20	67.69	65.81	229.67	23.89	90.01	100.89
Jamui	256.24	22.57	32.29	106.58	49.72	70.67	225.82	23.76	81.66	98.01
Khagaria	307.99	26.72	23.74	98.70	50.06	63.17	273.44	28.01	74.58	104.92
Lakhisarai	293.10	26.95	26.47	112.47	51.22	77.06	257.44	27.92	77.18	107.44
Munger	255.49	21.89	24.96	97.59	52.32	68.29	231.12	23.60	82.16	97.59
Sheikhpura	263.10	25.89	28.31	106.06	44.73	82.12	240.32	27.56	81.52	132.61
Subtropical Monsoon Climate (Cwa)										
Araria	337.26	20.66	20.38	98.82	82.5	46.10	305.02	22.65	84.69	98.16
Arwal	298.36	30.80	31.14	100.84	30.5	101.41	266.76	31.22	55.65	104.36
Aurangabad	260.86	24.09	33.71	94.45	26.75	79.99	236.18	24.75	57.65	97.48
Bhojpur	268.67	26.69	29.20	102.34	30.54	87.61	241.74	27.31	65.45	112.79
Buxar	245.54	25.39	32.08	113.44	29.89	96.35	228.46	26.90	85.87	146.07
Darbhanga	283.40	24.75	19.04	87.01	56.26	53.63	257.03	26.78	72.14	104.52
East Champaran	273.04	21.42	24.08	89.52	42.75	61.90	263.12	24.20	67.58	97.04
Gaya	258.94	24.59	30.77	90.55	69.21	83.69	235.51	25.71	54.70	86.47
Gopalganj	266.06	23.70	21.94	87.12	50.62	78.11	246.84	25.35	68.80	107.81
Jahanabad	276.03	27.75	30.56	96.65	33.45	126.84	256.83	29.54	50.40	97.13
Kaimur	257.19	24.76	31.02	93.92	28.9	106.85	240.71	25.98	51.37	98.73
Katihar	365.18	27.44	21.38	104.45	46.88	56.99	309.13	28.60	95.17	98.07
Kishanganj	468.15	21.65	21.52	101.72	52.86	42.77	438.92	24.36	103.14	99.39
Madhepura	295.83	22.85	20.31	101.68	75.4	57.24	265.16	24.72	85.68	102.93
Madhubani	280.60	23.09	18.22	94.86	100.72	48.57	260.75	25.60	70.39	102.93
Muzaffarpur	297.82	25.75	22.48	87.07	68.08	65.86	275.97	28.06	77.63	111.98
Nalanda	224.79	22.85	29.85	109.05	52.99	88.75	212.18	24.84	57.57	99.63
Nawada	213.66	21.14	30.59	99.48	51.32	90.96	189.68	21.96	73.01	102.20
Patna	247.62	24.95	26.94	98.41	39.42	88.18	225.49	26.32	58.95	98.10
Purnia	330.77	24.52	22.94	101.99	84.54	51.88	330.77	26.49	101.24	98.48
Rohtas	235.32	24.55	34.08	91.86	31.79	88.34	235.32	25.17	55.74	97.26

Saharsa	294.02	25.85	16.65	101.19	71.85	53.57	294.02	26.85	69.92	98.77
Samastipur	284.16	25.54	27.95	102.90	51.97	67.08	284.16	28.40	76.31	106.09
Saran	232.87	22.39	22.90	88.89	38.31	72.37	232.87	25.14	68.66	107.91
Sheohar	392.64	32.60	31.76	120.04	57.07	61.21	392.64	36.05	71.16	116.26
Sitamarhi	311.93	25.31	23.28	95.36	55.24	51.10	306.20	27.99	63.90	97.79
Siwan	250.18	24.77	26.34	96.87	39.12	77.14	250.18	26.85	84.44	131.68
Supaul	339.48	28.72	21.00	94.40	73.72	55.87	339.48	31.32	89.23	110.76
Vaishali	248.14	25.67	22.06	96.19	44.43	81.44	248.14	27.99	66.02	111.63
West Champaran	310.86	21.23	24.81	84.19	40.91	62.32	287.50	22.96	64.78	90.38

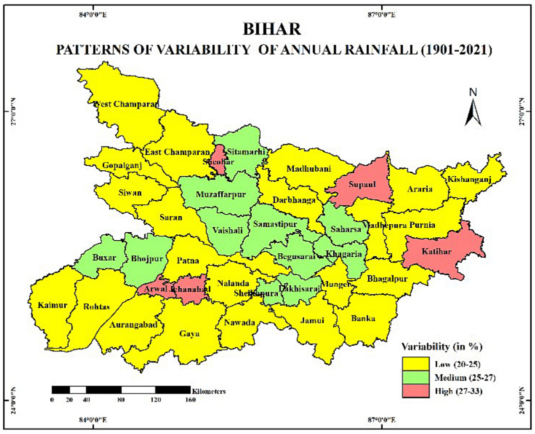


Fig. 3 a

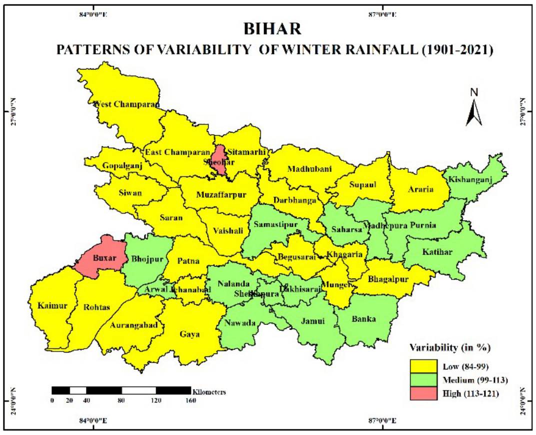


Fig. 3 b

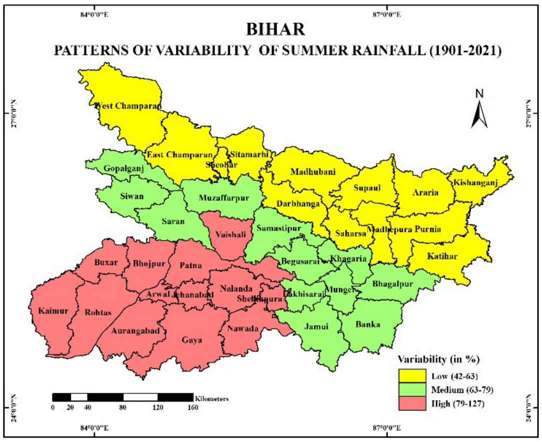


Fig. 3 c

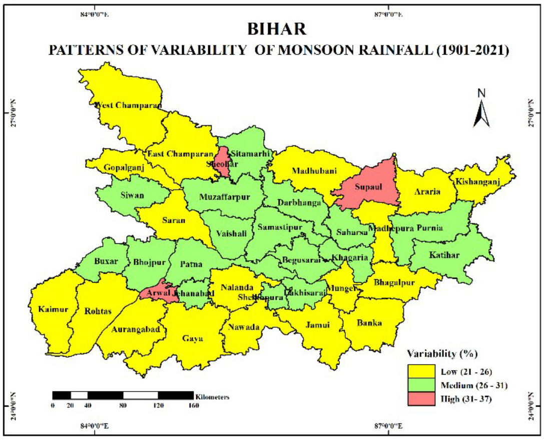


Fig. 3 d

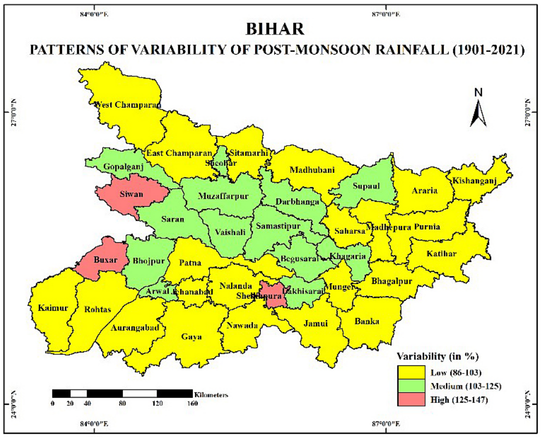


Fig. 3 e

Analysis of Annual and Seasonal Rainfall Trend

The analysis of rainfall trends from 1901 to 2021 across various stations in Bihar reveals notable declines in both tropical savanna (Aw) and subtropical monsoon (Cwa) climates, with distinct seasonal variations. In the tropical savanna climate, districts such as Begusarai, Lakhisarai, and Jamui exhibit significant negative trends in annual rainfall, with Z-scores of -2.04, -4.50, and -2.52, respectively. These correspond to annual declines of -1.71 mm/year, -4.04 mm/year, and -2.52 mm/year. Seasonal analysis indicates that summer and post-monsoon rainfall also follow declining trends in many of these stations.

In the subtropical monsoon climate, a more pronounced decline is observed, with stations like Arwal and Aurangabad showing significant Z-scores of -3.92 and -4.53, respectively, leading to annual rainfall decreases of -3.51 mm/year and -3.09 mm/year. Similar patterns are observed in Darbhanga and Madhubani, with Z-scores of -3.05 and -3.21, respectively.

Table 4: Rainfall Trends (1901-2021)

		Annual		Winter		Summer		Monsoon		Post-monsoon	
S. No	District	Z_S	Q_{med}	Z_S	Q_{med}	Z_S	Q_{med}	Z_S	Q_{med}	Z_S	Q_{med}
						Tropical Savanna Climate (Aw)					
1	Banka	-1.50	-1.07	-2.79	-0.16	-0.60	-0.08	-1.60	-1.01	0.34	0.05
2	Begusarai	-2.04	-1.71	-3.47	-0.18	-0.75	-0.10	-1.90	-1.44	0.17	0.02
3	Bhagalpur	-0.60	-0.42	-1.31	-0.06	1.48	0.27	-0.94	-0.57	0.72	0.11
4	Jamui	-2.52	-1.71	-4.38	-0.23	-2.11	0.26	-2.44	-1.44	0.42	0.06
5	Lakhisarai	-4.50	-4.04	-5.18	-0.22	-2.03	-0.25	-4.09	-3.13	0.85	0.12
6	Khagaria	-2.57	-2.36	-3.62	-0.18	0.58	0.09	-2.80	-2.22	0.96	0.11
7	Munger	-2.39	-1.74	-3.75	0.17	-0.47	-0.05	-2.25	-1.33	-0.01	0.00
8	Sheikhpura	-3.08	-2.32	-3.53	-0.18	-0.92	-0.10	-3.37	-2.33	0.66	0.07
						Subtropical Monsoon Climate (Cwa)					
9	Arwal	-3.92	-3.51	-2.80	-0.18	-0.12	-0.01	-3.90	-3.27	-1.22	-0.12
10	Araria	-3.08	-0.45	-2.79	-0.16	0.72	0.17	-3.34	-0.31	-1.11	-0.15

11	Aurangabad	-4.53	-3.09	-2.72	-0.17	-0.92	-0.06	-4.37	-2.70	-0.62	-0.06
12	Kaimur	-2.29	-1.46	-2.32	-0.14	-0.53	-0.02	-1.92	-1.06	-1.48	-0.11
13	Bhojpur	-2.46	-2.46	-3.10	-0.15	1.57	0.11	-2.72	-1.50	-1.20	-0.11
14	Buxar	-2.77	-1.92	-4.03	-0.21	-0.16	-0.01	-2.22	-1.41	-1.50	-0.14
15	Darbhanga	-3.05	-2.37	-1.65	-0.06	0.74	0.10	-3.26	-2.25	-0.48	-0.05
16	East Champaran	-2.35	-1.85	-1.30	-0.07	0.48	0.07	-2.39	-1.73	-0.76	-0.08
17	Gaya	-4.12	-2.81	-3.57	0.99	0.02	0.00	-3.81	-2.56	-0.90	-0.10
18	Gopalganj	-1.73	-1.28	-1.87	-0.07	1.42	0.16	-1.74	-1.21	-1.04	-0.11
19	Jahanabad	-2.83	-2.26	-3.06	-0.21	0.25	0.02	-2.83	-2.10	-0.61	-0.05
20	Katihar	-0.05	-0.04	-1.19	-0.03	1.66	0.34	0.68	-0.58	0.27	0.04
21	Kishanganj	-0.80	-1.04	-2.94	-0.11	-0.11	-0.02	-0.21	-0.26	-1.52	0.26
22	Madhepura	-1.20	-1.08	-1.20	-0.05	2.56	0.58	-1.62	-1.50	-0.59	-0.10
23	Madhubani	-3.21	-2.57	-1.52	-0.05	-0.51	-0.08	-2.91	-2.09	-2.06	-0.20
24	Muzaffarpur	-1.30	-1.13	-1.37	-0.06	2.06	0.26	-1.53	-1.17	-0.76	-0.09
25	Nalanda	-0.57	-0.41	-2.82	-0.12	1.09	0.09	-0.94	-0.54	0.23	0.02
26	Nawada	-2.02	-1.27	-3.14	-0.17	0.09	0.01	-2.04	-1.14	0.38	0.03
27	Patna	-0.69	-0.43	-2.38	-0.11	2.52	0.21	-1.28	-0.80	-0.12	-0.01
28	Purnia	2.12	2.18	-1.86	-0.07	3.90	0.79	1.33	1.20	0.78	0.12
29	Rohtas	-4.66	-3.21	-3.16	-0.19	0.61	0.04	-4.61	-2.76	-1.49	-0.16
30	Saharsa	-3.61	-3.13	-0.68	-0.00	-2.05	-0.42	-3.64	-2.56	0.89	-0.09
31	Samastipur	-2.08	-1.68	-2.08	-0.09	1.74	0.24	-2.52	-1.94	0.35	-0.05
32	Saran	-1.52	-1.01	-1.30	-0.06	1.11	0.10	-1.59	-1.03	-0.88	-0.09
33	Sheohar	-0.25	-0.33	-0.72	-0.03	0.31	0.05	-0.32	-0.38	-1.00	-0.06
34	Sitamarhi	-2.00	-1.85	-1.86	-0.08	-0.94	-0.14	-1.87	-1.45	-1.84	0.19
35	Siwan	-1.24	-0.99	-3.03	-0.15	0.99	0.10	-1.99	-1.35	-1.12	-0.11
36	Supaul	-1.70	-1.52	-1.69	-0.07	-1.65	-1.36	1.14	0.24	-0.88	-0.08
37	Vaishali	-2.15	-1.63	-2.95	-0.13	1.41	0.14	-2.10	-1.52	-0.20	-0.02
38	West Champaran	0.24	0.20	-1.13	-0.05	2.71	0.48	-2.22	-0.07	-0.27	-0.03

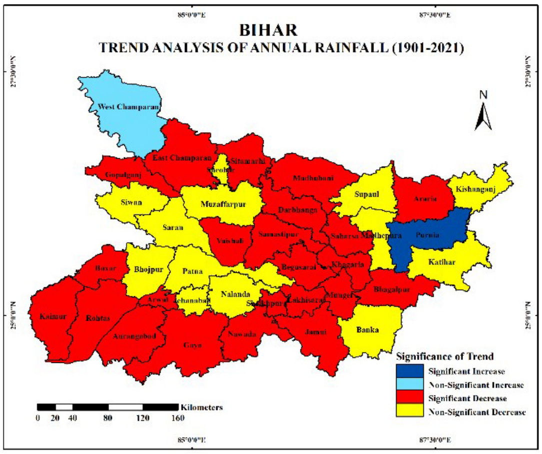


Fig. 4 a

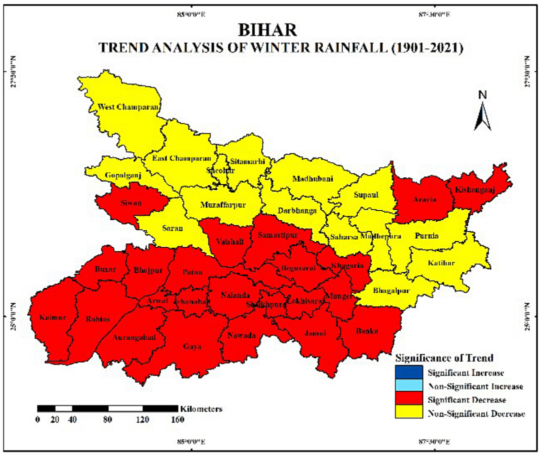
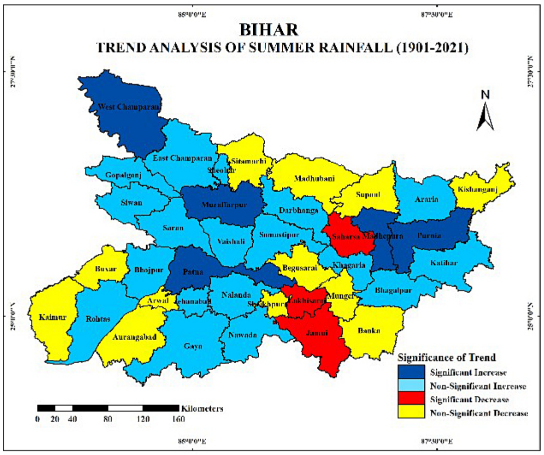


Fig. 4 b



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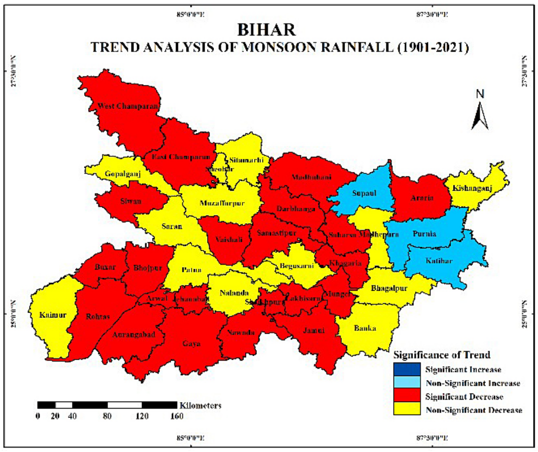

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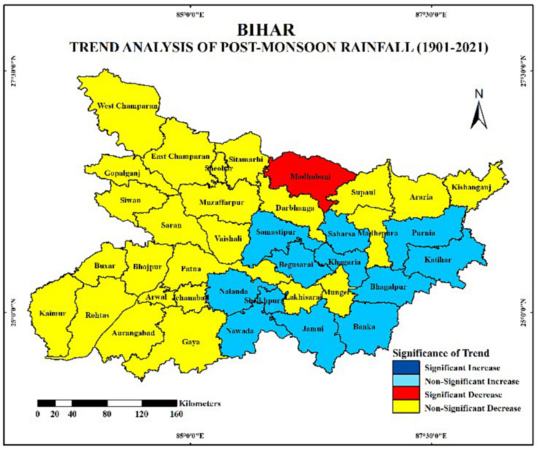

Fig. 4 e

Table 5: Average SPI (1901-2021)

District	SPI 3	SPI 6	SPI 9	SPI 12
Tropical Savanna Climate (Aw)				
Banka	0.001	0.001	0.000	0.000
Begusarai	0.002	0.001	0.002	0.000
Bhagalpur	0.001	0.001	0.001	-0.001
Jamui	0.002	0.002	0.000	0.001
Khagaria	0.003	0.003	0.001	0.001
Lakhisarai	0.002	0.002	0.002	0.001
Munger	0.001	0.001	0.000	-0.001
Sheikhpura	0.002	0.002	0.001	0.001
Subtropical Monsoon Climate (Cwa)				
Araria	0.000	0.000	0.001	0.000

Arwal	0.000	0.000	0.000	0.000
Aurangabad	0.001	0.001	0.001	0.000
Bhojpur	0.009	0.008	0.007	0.006
Buxar	0.003	0.003	0.003	0.000
Darbhanga	0.000	0.001	0.000	0.000
East Champaran	0.001	0.001	0.001	0.002
Gaya	0.000	0.000	0.000	0.000
Gopalganj	0.000	-0.001	0.000	0.000
Jahanabad	0.001	0.002	0.000	0.000
Kaimur	0.001	0.001	0.000	0.002
Katihar	0.001	0.000	0.000	0.000
Kishanganj	0.001	0.001	0.001	0.000
Madhepura	0.000	0.001	0.001	0.000
Madhubani	0.001	0.001	0.000	0.001
Muzaffarpur	0.000	0.001	0.000	0.000
Nalanda	0.000	0.001	0.000	0.001
Nawada	0.000	0.001	0.000	0.001
Patna	0.000	0.001	0.000	0.000
Purnia	0.000	0.001	0.001	0.000
Rohtas	0.001	0.001	0.001	0.001
Saharsa	0.001	0.001	0.001	0.000
Samastipur	0.001	0.001	0.001	0.000
Saran	0.001	0.001	0.001	0.002
Supaul	0.009	0.009	0.006	0.009
Sheohar	0.001	0.001	0.000	0.001
Sitamarhi	0.017	0.019	0.007	0.013
Siwan	0.001	0.001	0.001	0.001
Vaishali	0.013	0.009	0.006	0.003
West Champaran	0.000	0.000	0.000	0.000

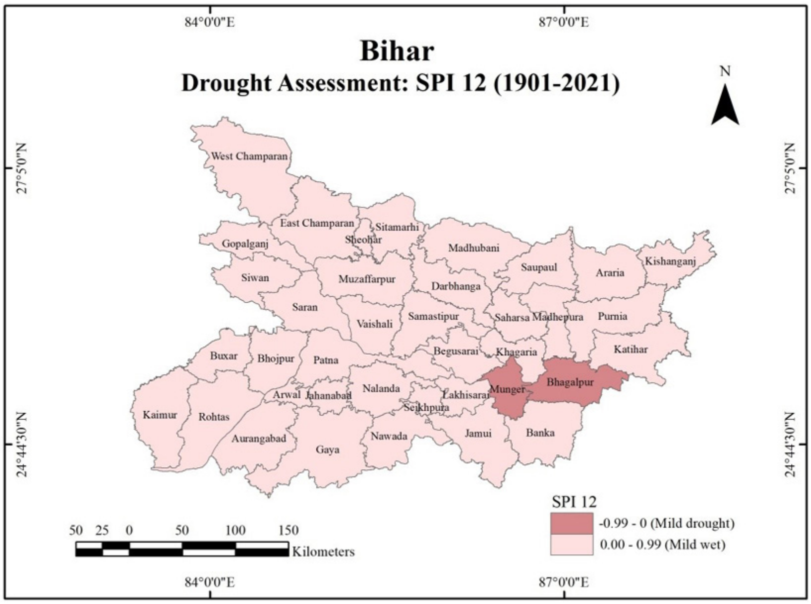

Fig. 5: Drought Assessment using SPI12

Drought Assessment Using SPI

Analyzing Standardized Precipitation Index (SPI) values for Bihar from 1901 to 2021 provides insights into drought patterns across different time scales. The 3-month SPI, reflecting short- and medium-term moisture conditions, shows a generally uniform rainfall distribution across the state. The 6- and 9-month SPI values follow a similar pattern, with Gopalganj being the only notable outlier. The 12-month SPI reveals that southeastern districts like Bhagalpur and Munger have experienced mild drought, while the rest of Bihar has remained mildly wet. Minimal differences in SPI values are observed across the region, with most districts receiving over 1100 mm of annual rainfall. Overall, Bihar tends to experience more intense wet periods than dry ones, with a largely consistent rainfall distribution. These findings are supported by Table 5 and the corresponding maps, which illustrate the spatial variability of rainfall and drought conditions.

Discussion

The observed spatial and seasonal variability in rainfall across Bihar is largely influenced by topographical factors, monsoonal circulation, and climate patterns. The higher rainfall in northeastern districts is attributed to their proximity to the Himalayas and the Bay of Bengal, which enhance orographic lift and moisture availability. In contrast, the southwest experiences a decline in rainfall due to the rain-shadow effect and diminishing monsoonal influence. The monsoon, contributing 80% of annual rainfall, underscores the region's dependence on monsoonal precipitation for agriculture. However, rising rainfall extremes, such as increased heavy rainfall events and prolonged dry spells, pose significant challenges for water resource management and disaster preparedness. Studies highlight increasing drought occurrences in southern Bihar, aligning with the present findings that show lower annual rainfall in southwestern districts.[20] Seasonal variations in rainfall further indicate potential risks to agriculture, with winter and summer rainfall variability affecting rabi and *kharif* crop production.[21] This necessitates adaptive farming strategies, including drought-resistant crops and improved irrigation systems. The rainfall differences between the Cwa and Aw climatic zones suggest that areas with a tropical savanna climate (Aw) may require additional water management strategies to sustain agriculture.

In the Aw region, the relatively stable monsoonal rainfall supports *Kharif* crop cultivation, with low SD values in monsoon rainfall (e.g., Bhagalpur and Jamui), indicating a predictable water supply that supports consistent agricultural output. However, post-monsoon and winter variability, as seen in Sheikhpura and Jamui, poses challenges for Rabi crop irrigation, highlighting the need for better soil moisture retention techniques and irrigation planning. A previous study found less monsoon variability in the Aw region, further supporting the idea that this climate type provides more stable rainfall patterns for agriculture.[22] Conversely, the Cwa region exhibits high variability across all seasons, especially in monsoon and winter rainfall. Stations like Kishanganj, Araria, and Purnia experience extreme fluctuations in monsoon SD, which increases flood risks and threatens food security. The high SD values in monsoon rainfall (e.g., Kishanganj: 438.92) call for improved flood mitigation and drainage systems. Additionally, winter rainfall variability in Buxar and Arwal (CV >100%) suggests challenges for groundwater recharge and irrigation management. These findings are consistent with previous research which emphasized the higher variability in Cwa regions, particularly during monsoon and winter seasons, requiring more efficient water management practices. Furthermore, significant inter-annual fluctuations in summer rainfall (e.g., Supaul and Sitamarhi) can impact early cropping cycles and water storage planning, as highlighted by another study which stressed the urgent need for adaptive water management strategies in the Cwa region to mitigate rainfall variability risks.[23]

Overall, the findings suggest that while farmers in the Aw region benefit from stable monsoon rainfall for reliable *Kharif* cultivation, the Cwa region's high rainfall variability during monsoon and winter demands improved water management practices to reduce agricultural and hydrological risks. The declining rainfall trends in both tropical savanna and subtropical monsoon climates highlight the need for timely water management strategies. The findings emphasize the importance of adaptive measures, such as better irrigation systems and drought-resistant crops, to address the challenges posed by changing rainfall patterns in Bihar.

Conclusion

The analysis of rainfall patterns in Bihar reveals significant spatial variability, with a pronounced decline in precipitation as one move from the northeastern to the southwestern parts of the state. North Bihar experiences considerably higher rainfall compared to its southern counterpart, which holds critical implications for agricultural productivity in both regions. In subtropical monsoon climate zones like Bihar, rainfall fluctuations are more pronounced than in tropical savanna zones, leading to unpredictable growing conditions that farmers must navigate. A troubling trend is the observed decline in monsoon rainfall, which is vital for the *Kharif* crop season which primarily relies on this precipitation for sustaining crops like rice and pulses. This reduction poses a direct threat to agricultural yields and food security, underscoring the urgency for adaptive measures. Conversely, the increasing summer rainfall (while potentially beneficial) highlights the need for enhanced water storage systems to capture and retain this precipitation effectively. Existing infrastructure may not suffice to manage these new patterns of rainfall, leading to runoff and wastage. Moreover, reduced rainfall during the winter and post-monsoon periods, particularly in southern Bihar, further exacerbates challenges for Rabi crops that are reliant on consistent moisture levels for their growth. The analysis also reveals that mild wet conditions prevail in the region, with specific districts facing occasional mild droughts, illustrating the complex interplay of rainfall dynamics across Bihar. The standardized precipitation index (SPI) values, which indicate a uniform pattern of precipitation variability, reinforce the importance of strategic water resource management.

Strategies like rainwater harvesting, improved irrigation, drought-resistant crops, and weather forecasting are vital for agricultural resilience. Investments in water conservation measures based on nature-based solutions like maintenance of natural embankments and check dams, recharging of ponds, and promoting community-based water management can build resilience and mitigate the impacts of climate variability. Combining traditional Indian knowledge systems with modern technology offers a holistic approach to water management.

In summary, Bihar must adopt a multi-faceted approach-a combination of advanced water management, adaptive farming, and community engagement to enhance agricultural resilience and ensure sustainability amid changing rainfall patterns.

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Conflict of Interest

The authors do not have any conflict of interest.

Data Availability Statement

The meteorological data used in this study has been provided by India Meteorological Department (IMD), Patna on monthly and annual time scale.

Ethics Statement

This research did not involve human participants, animal subjects, or any material that requires ethical approval.

Informed Consent Statement

This study did not involve human participants, and therefore, informed consent was not required.

Permission to Reproduce Material from Other Sources

Not Applicable

Author Contributions

- **Manu Raj Sharma:** conceptualization, methodology, software, validation;
- **Sukeshi Priya:** data mapping, writing—original draft preparation, data analysis, and restructuring;
- **Surbhi Kumari:** Analysis of SPI, supervision, revision.

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