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Research Article

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Posted Date: September 21st, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10846905/v1>

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Additional Declarations: No competing interests reported.

Multi-Hazard Climate Extremes and Risk in Bihar (India): Vulnerability, Climate-Resilient Adaptation and Institutional Responses

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Abstract

Climate extremes increasingly influence environmental, agricultural, hydrological, health, and socioeconomic risks in vulnerable regions. Bihar, a densely populated and largely agrarian state in India, faces heightened exposure to heat waves, heavy rainfall, floods, and droughts because of its reliance on monsoon rainfall, fragile water resources, and limited adaptive capacity. Despite this vulnerability, detailed long-term assessments of multi-hazard climate risks at the district level remain lacking. This study fills that gap by using a multidisciplinary approach that combines long-term climate data with risk, vulnerability, and resilience analyses to guide policy decisions.

The study examines high-resolution district-level meteorological datasets from the India Meteorological Department (IMD), ERA reanalysis, and the Copernicus Climate Data Store, covering precipitation data from 1901 to 2021 and temperature data from 1951 to 2024. Climate extremes and risk patterns are analysed using 24 ETCCDI-recommended indices for temperature and rainfall, using GIS and Python tools to map district exposure across Bihar. Results show a significant warming trend and a slight decline in annual rainfall, alongside notable shifts in extreme events. The number of consecutive dry days (CDD) is rising significantly, reaching 85–105 days annually in central and southern districts, increasing drought and groundwater depletion risks. Meanwhile, northern districts are experiencing more frequent and intense heavy rainfall, leading to recurring floods and a complex hazard landscape across Bihar.

Assessing district exposure, sensitivity, and institutional response shows Bihar has shifted from reactive relief efforts to proactive preparedness and resilience strategies. However, gaps remain

due to fragmented institutional responsibilities, uneven adaptive capacity at the district level, limited access to climate finance, and social vulnerabilities. Addressing these issues requires moving toward an integrated, multidisciplinary approach that manages complex climate risks across sectors, landscapes, and administrative levels. These insights provide context-specific pathways for evidence-based decision-making and climate-resilient policies in Bihar's most at-risk districts.

Keywords: *Adaptation Strategies; Climate Resilience; District-Level Assessment; Extreme Rainfall Indices; Interdisciplinary Climate Research; Multi-Hazard Risk Assessment; Nature-Based Solutions; Socioeconomic Vulnerability; Spatio-Temporal Climate Analysis; Weather Extremes.*

1. Introduction

Weather and climate extremes have increasingly reshaped Earth's climate and hydrological systems, with far-reaching consequences for natural environments and human societies, and have emerged as a major challenge to sustainable development. These changes are largely driven by anthropogenic activities, including fossil-fuel combustion, industrial expansion, and land-use modification, which have altered the atmospheric energy balance and contributed to long-term climate change [15,16]. One major outcome of these changes is the increasing occurrence and intensity of extreme hydro-climatic events, including intense precipitation, floods, prolonged droughts, and extreme heat [17]. Long-term analysis is essential to determine whether recent extreme events reflect natural climate variability or indicate a shift from historical patterns. Century-scale studies therefore provide an important historical baseline for understanding and assessing contemporary climate conditions and their changing extremes [13,14].

The consequences of hydro-climatic extremes extend beyond physical hydrological systems. Altered rainfall regimes and rising temperatures place additional stress on ecosystems, agriculture, and biodiversity, while also increasing risks to human health and livelihoods [17,35,36]. Social impacts are particularly significant because communities with limited adaptive capacity face greater exposure to climate-related hazards, livelihood instability, and displacement. Climate change can therefore amplify existing social and economic vulnerabilities, resulting in uneven impacts across regions and population groups [17]. Evidence from western North America illustrates the importance of long-term hydro-climatic

variability. Reconstructions of California's hydro-climate indicate substantial variability in winter, spring, and summer conditions during the period 1940–2019, demonstrating the importance of historical variability in understanding contemporary hydro-climatic extremes [30]. More broadly, global evidence indicates that both wet and dry regions have experienced changes in precipitation extremes, highlighting the increasing significance of intense precipitation events [5].

In the South Asian context, hydro-climatic responses vary substantially across space. Research on the Subarnarekha River Basin in eastern India found considerable rainfall variability and exposure to extreme rainfall events, emphasizing that changes in precipitation characteristics can be important even where long-term trends in annual rainfall are weak or statistically insignificant [25]. Such variability is particularly relevant for monsoon-dependent regions, where changes in the timing, intensity, and distribution of rainfall can strongly influence flood risk, water availability, and agricultural productivity. Studies of Indian hydro-climatic conditions similarly emphasize substantial regional differences in observed climate variability and change [13,14].

In India, weather and climate extremes have emerged as critical environmental and developmental challenges because a substantial proportion of the population remains dependent on climate-sensitive sectors, particularly agriculture and water resources. Observational assessments indicate a long-term warming tendency across the Indian region, accompanied by substantial variability and changes in precipitation characteristics [14,16]. These changes, combined with recurrent temperature extremes, increase stress on agricultural systems and can adversely affect crop productivity and rural livelihoods. Climate change impacts on wheat production in India, for example, demonstrate the sensitivity of agricultural productivity to changing temperature and precipitation conditions [26]. Altered rainfall regimes can further increase uncertainty in water availability and agricultural production, particularly in regions dependent on monsoon rainfall. Beyond agriculture, weather and climate extremes pose significant public-health risks, including heat-related impacts and climate-sensitive infectious diseases associated with changing environmental and hydrological conditions [17,35]. Recognising these threats, India has developed a range of policy responses, including the National Action Plan on Climate Change (NAPCC), which provides a national framework for addressing climate mitigation and adaptation [32]. State-level climate action plans further support region-specific adaptation and resilience strategies [33].

In eastern India, and particularly in flood-prone and agrarian regions such as Bihar, century-scale assessments of hydro-climatic variability and extremes remain particularly important. Understanding these changes over long periods provides a basis for improved water management, climate adaptation, agricultural planning, and disaster-risk reduction. Bihar is highly sensitive to weather and climate extremes because of its dependence on agriculture, exposure to recurrent floods and droughts, and substantial socio-economic vulnerability. The state has also been identified as a region requiring strengthened climate resilience through coordinated adaptation and development interventions [8]. Long-term assessments of climate variability over the Indian region indicate persistent warming and substantial regional differences in temperature and precipitation changes [14,16]. Such changes have important implications for agriculture in Bihar, particularly for crops such as wheat that are sensitive to temperature and moisture conditions [26].

Rainfall variability represents another major climate-related challenge in Bihar. Recent studies have documented substantial spatial and temporal variability in precipitation across the state and have highlighted the importance of extreme rainfall events in understanding regional hydro-climatic risk [27]. Changes in precipitation characteristics can increase the likelihood of intense rainfall and associated flooding in vulnerable areas, while rainfall deficits and prolonged dry periods can increase agricultural and water stress. Bihar's high sensitivity to natural hazards further increases the importance of integrated assessments of climate extremes. Geoinformatics-based hazard assessments have demonstrated the state's exposure to multiple natural hazards, while recent research has also highlighted its seismic vulnerability [7,38]. Consequently, climate-related hazards need to be considered within a broader multi-hazard framework rather than as isolated environmental processes.

Small and marginal farmers in Bihar are particularly vulnerable to weather and climate extremes because of their dependence on rainfall, limited irrigation facilities, small landholdings, and restricted economic capacity. Vulnerability assessments in Bihar have demonstrated substantial exposure and sensitivity of farming communities to climate variability, particularly in climate-sensitive agricultural regions [19]. Rising temperatures and associated heat stress can also affect livestock productivity, creating additional challenges for rural households dependent on livestock-based livelihoods [18]. These agricultural and livestock impacts are compounded by Bihar's exposure to recurrent hydro-meteorological hazards, particularly floods and droughts. The Bihar State Action Plan on Climate Change

identifies the need to strengthen resilience through climate-sensitive development and adaptation measures [8].

Changes in rainfall can contribute to both flood and drought risks, depending on their magnitude, timing, duration, and spatial distribution. Research on hydrological extremes shows that hydro-climatic regimes can change substantially in the characteristics and frequency of extreme events under changing climatic conditions [24]. Global assessments have similarly reported increasing precipitation extremes across several climatic regions [5]. These changes are particularly important for Bihar, where agricultural production, water resources, and rural livelihoods are closely linked to monsoon behaviour. Strengthening climate-resilient agriculture, improving water-resource management, developing effective early-warning systems, and enhancing institutional and community-level preparedness are therefore essential components of climate adaptation. Bihar's policy initiatives, including the State Action Plan on Climate Change and the Jal-Jeevan-Hariyali Mission, provide important institutional frameworks for strengthening environmental sustainability and climate resilience [8,12].

Climate adaptation, however, remains challenging because of increasing climatic variability, compound hazards, uncertainty in future projections, and differences in adaptive capacity across regions and communities [17]. Strengthening policies, financial resources, institutional coordination, scientific assessment, and local implementation is therefore essential for achieving climate-resilient development in India. Recent assessments of climate variability and policy responses emphasize the importance of integrating scientific evidence with sector-specific adaptation and long-term planning [6,14,16]. At the state level, climate-resilience initiatives must align with local environmental conditions, livelihood systems, and disaster vulnerabilities.

Against this background, the present study analyses long-term hydro-climatic variability and extremes in Bihar using century-scale observational records to establish historical baselines and characterize changes in the frequency, intensity, and persistence of climate extremes. It further examines the implications of changing hydro-climatic conditions for agriculture, water resources, and climate-risk management. By integrating long-term observations with an assessment of hydro-climatic extremes, the study seeks to provide a robust evidence base for understanding climate variability in Bihar and supporting climate-resilient planning, adaptation, and resource management.

2. Objectives

This study analyses long-term temperature and precipitation data across Bihar to understand the spatial and temporal patterns of climate extremes. It identifies district-level hotspots for temperature, precipitation, drought, and compound hazards, and assesses regional exposure, sensitivity, and adaptive capacity in sectors such as agriculture, water, health, and settlements. The research also examines current adaptation, mitigation, and disaster risk responses to identify institutional, financial, technical, and social gaps. These insights help develop tailored, climate-resilient strategies and policies to boost local resilience and inform decision-making in vulnerable districts.

3. Study Area

Bihar is in eastern India, with a geographical location ranging from 24°20' to 27°31' N latitude and 83°19' to 88°17' E longitude, covering about 94,163 km². The state shares its boundaries with Nepal in the north, Uttar Pradesh in the west, Jharkhand in the south, and West Bengal in the east. The geographical features of the state include the Gangetic plains in the northern and central parts, which are fertile, while the southern part is characterized by undulating plateaus. Bihar has a tropical monsoon climate with hot summers, a humid southwest monsoon season, and cold winters. Summers are hot, with high humidity during the southwest monsoon season, and winters are cold. The monsoon season, which lasts from June to September, receives about 80-85% of the total annual rainfall. This makes agriculture extremely monsoon-dependent. Temperature varies widely, with frequent heat waves in summer and cold waves in winter, especially in the northern and central parts of the state.

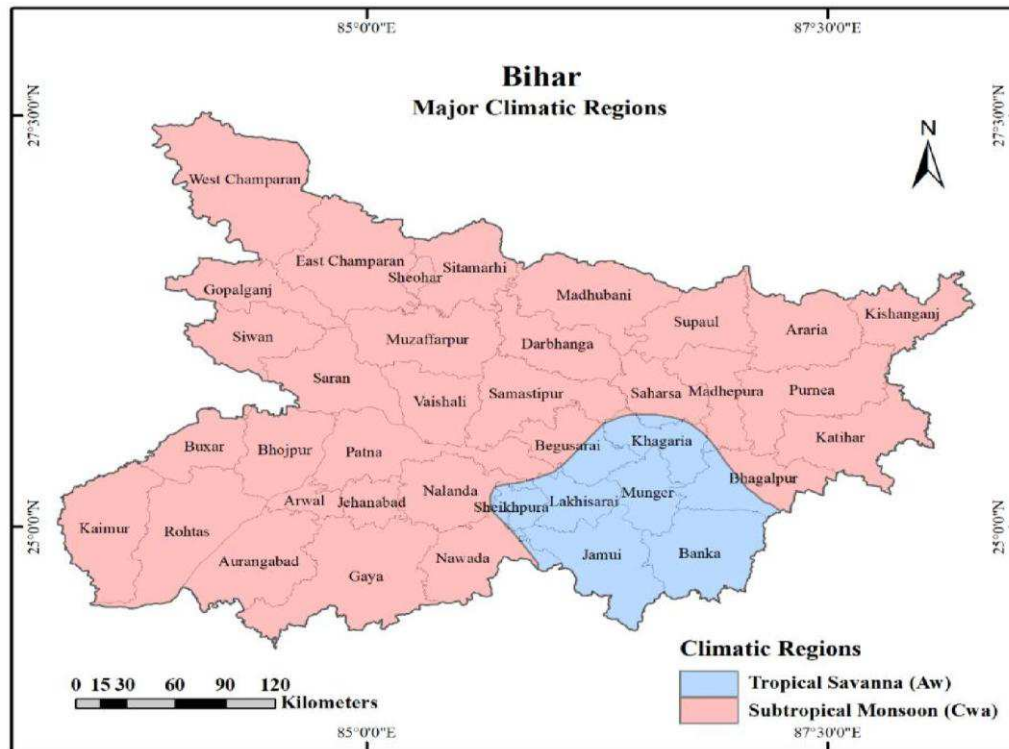


Fig 1: Climate Regions of Bihar; Source: (India Meteorological Department, 2011)

Agriculture is the mainstay of Bihar's economy and employs many people. The high population density, rural dependence, and low adaptability make the state highly vulnerable to hydro-climatic extremes. Recurrent floods and droughts disrupt crop production, damage infrastructure, and trigger seasonal migration, underscoring the importance of region-specific climate risk assessments.

4. Data Sources and Methodology

This study uses high-quality observational and reanalysis datasets to ensure robust, spatially consistent hydro-climatic analysis. Monthly and annual precipitation data for the period 1901–2021 and maximum and minimum temperature data for 1951–2024 were obtained from the India Meteorological Department (IMD) in station-based and gridded formats at $\sim 0.5^\circ$ spatial resolution. Daily temperature and precipitation records were used to compute climate extreme indices following the guidelines of the Expert Team on Climate Change Detection and Indices (ETCCDI). ERA-based reanalysis products from the Copernicus Climate Data Store were additionally used to improve spatial completeness and long-term consistency (Fig. 2)

All datasets were subjected to standard quality control procedures, including outlier detection, consistency checks, homogenization, and gap-filling, to minimize non-climatic biases in long-term time series. Hydro-climatic variability was assessed using annual and seasonal precipitation totals and mean, maximum, and minimum temperature series, with seasonal analysis focusing on monsoon, winter, summer, and post-monsoon periods. Climate extremes were quantified using ETCCDI indices such as CDD, CWD, R10mm, R20mm, R25mm, PRCPTOT, RX1DAY, RX5DAY, SDII, and R95p/R99p, capturing changes in the frequency, intensity, and persistence of extreme rainfall events. Trends in temperature and precipitation indices were assessed using the non-parametric Mann–Kendall (Mann, 1945) test to detect monotonic trends at the 95% confidence level. The magnitude of trends was estimated using Sen’s slope estimator (Sen, 1968). Prior to trend analysis, time series were tested for serial autocorrelation, and necessary procedures were applied to avoid overestimation of significance. Statistical analyses were performed using R and Python, and spatial interpolation and district-level mapping were conducted using ArcGIS.

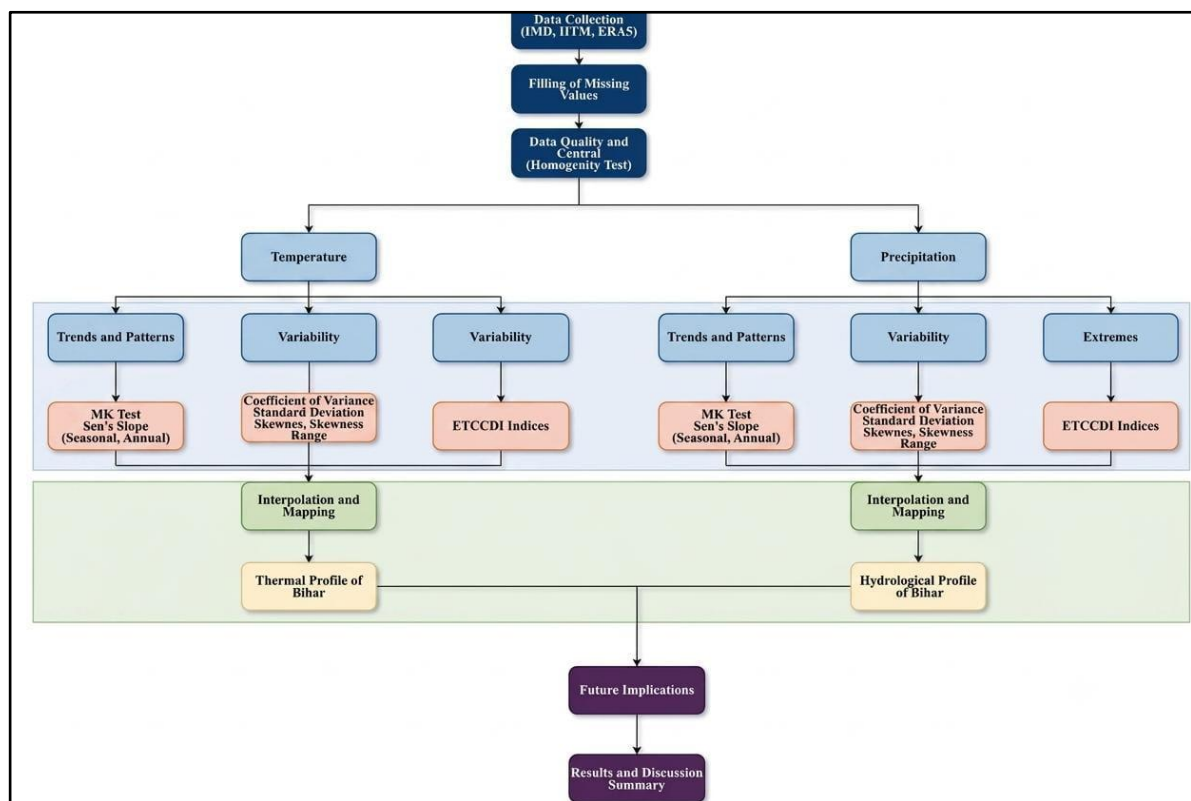
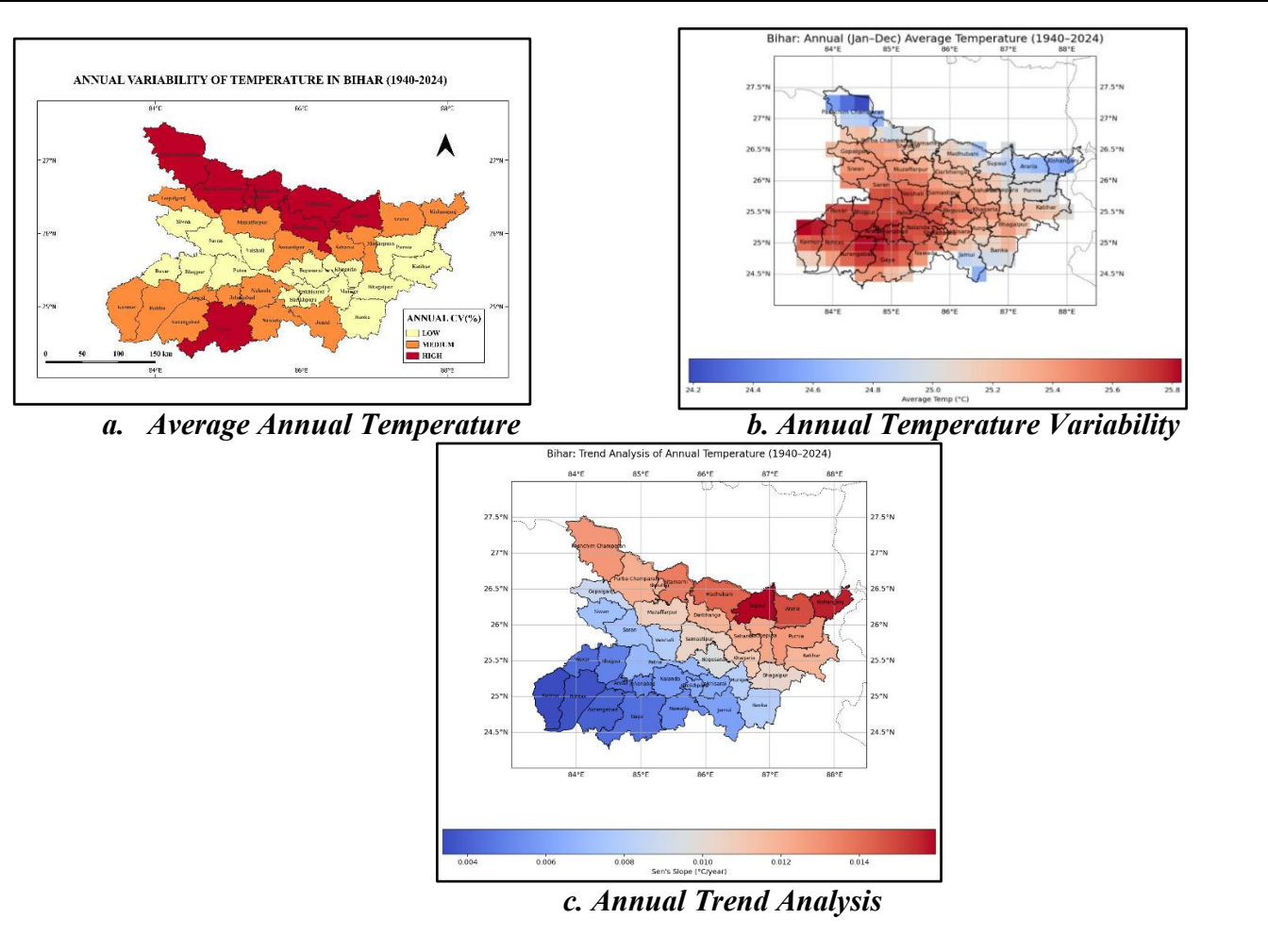


Fig 2: Flowchart of Data Sources and Research Methodology

213 **5. Results: Long-term climate observations**

214 **5.1. Annual and Seasonal Temperature Pattern, Variability, and Trend**



215 **Fig 3: Annual Temperature Pattern, Variability, and Trends**

216 The analysis of long-term annual temperature records (1940–2024) across Bihar reveals a
217 pronounced north–south and east–west thermal gradient. Northern and north-eastern districts
218 such as Kishanganj (24.59°C), Pashchim Champaran (24.71°C), Supaul (24.91°C), and Araria
219 record the lowest mean annual temperatures, whereas higher values are observed in
220 southwestern and south-central districts including Arwal (25.77°C), Aurangabad (25.71°C),
221 Bhojpur (25.71°C), Rohtas (25.64°C), Gaya (25.55°C), and Patna (25.66°C). Across all
222 districts, mean annual temperatures range from 24.59°C to 25.77°C. Measures of variability
223 indicate relatively low coefficients of variation (2.13%–2.52%), suggesting long-term thermal
224 stability, although annual temperature ranges vary considerably, with Gaya recording the
225 highest range (3.7°C). Trend analysis identifies statistically significant positive trends in 33 of

the 38 districts. Higher Z-scores and Sen's Slope values are concentrated in northern and north-eastern districts. Time-series analysis indicates an overall increase in annual mean temperature of approximately 0.8°C–1.2°C over the study period, with accelerated warming evident after the 1980s.

5.2 Winter Temperature Characteristics

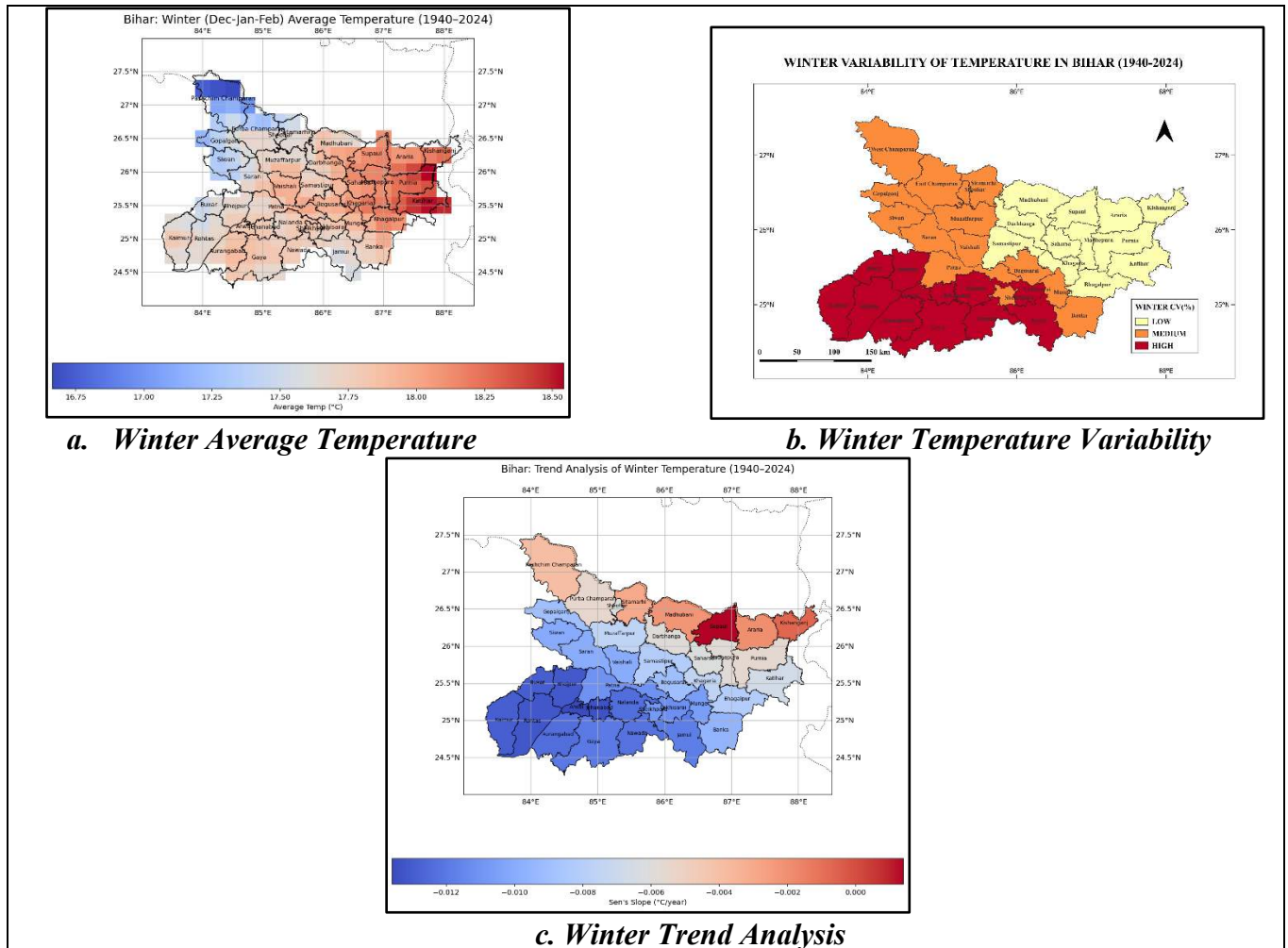


Fig 4: Winter Temperature Pattern, Variability, and Trend; Source: Prepared by authors

Winter (December–February) temperatures display a clear east–west gradient across Bihar. Eastern and north-eastern districts, including Katihar, Purnia, Araria, and Kishanganj, record higher mean winter temperatures exceeding 18.2°C, while western and north-western districts such as West Champaran, Siwan, Gopalganj, Buxar, and Kaimur record mean values below 17.3°C. Central districts show intermediate temperatures (17.5°C–18.0°C) but exhibit the largest winter temperature ranges, reaching up to 3.6°C in districts such as Kaimur and Arwal. Variability indicators reveal higher coefficients of variation in southern and south-western

districts, whereas north-eastern districts display relatively stable winter temperatures. Trend analysis shows statistically significant decreasing trends in winter temperature across several districts, particularly in the southern and south-western regions, with Sen's Slope values close to -0.01°C per year. In contrast, most north-eastern districts show non-significant trends.

5.3 Pre-Monsoon Temperature Characteristics

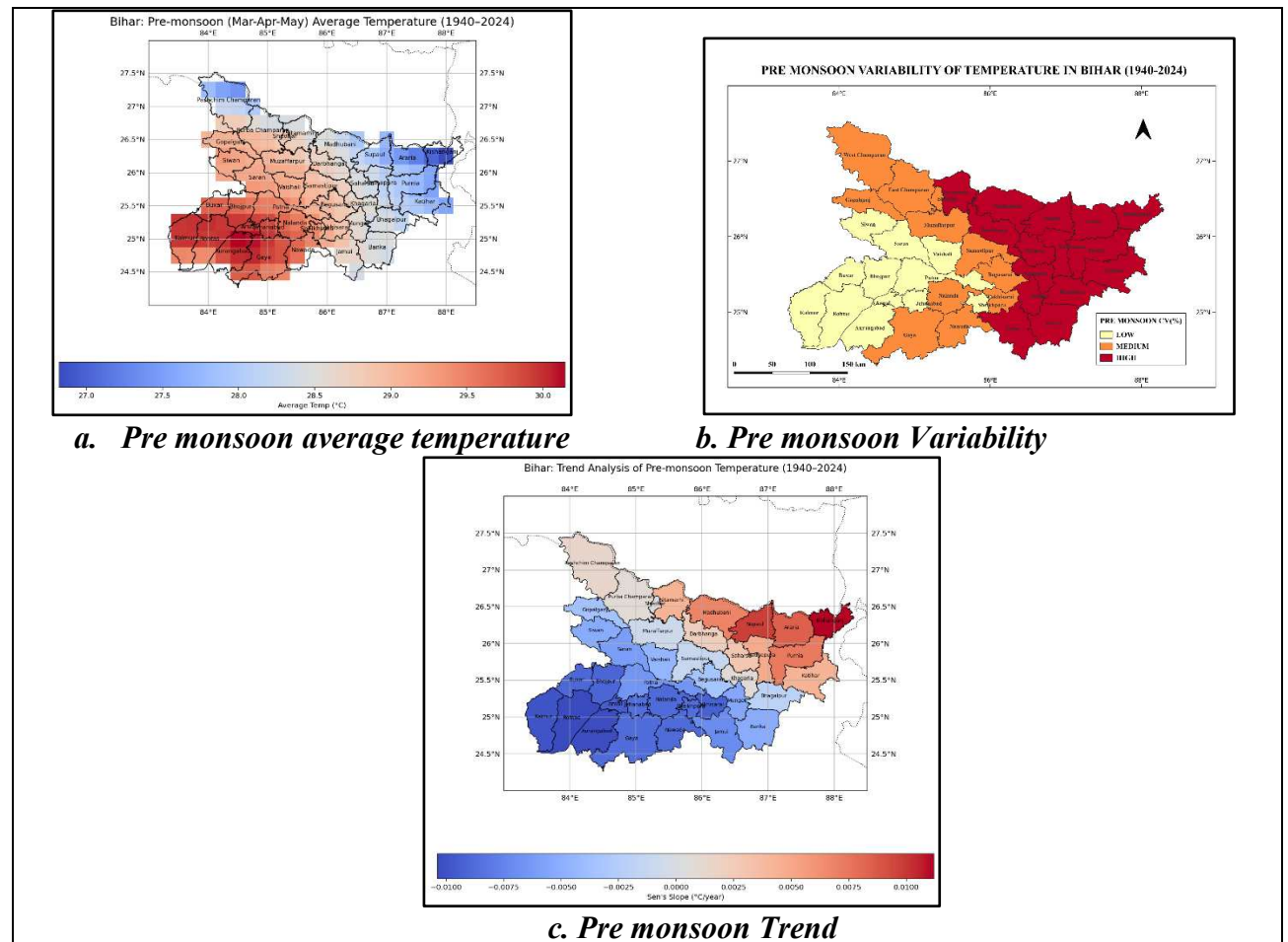


Fig 5: Pre Monsoon Temperature Pattern, Variability, and Trend; Source: Prepared by authors

Pre-monsoon (March–May) temperatures show strong spatial contrasts across Bihar. Central and south-western districts such as Aurangabad (29.99°C), Arwal (29.90°C), and Rohtas (29.86°C) record the highest mean temperatures, while north-eastern districts including Kishanganj (26.92°C), Katihar (27.78°C), and Purnia (27.76°C) record comparatively lower values. Temperature ranges during this season exceed 7°C in districts such as Gaya, Aurangabad, and Rohtas. Variability analysis indicates higher coefficients of variation in eastern and north-central districts, with relatively lower variability in western and south-

western districts. Trend analysis shows predominantly non-significant trends across most districts, with Kishanganj as the only district exhibiting a statistically significant increasing trend.

5.4 Monsoon Temperature Characteristics

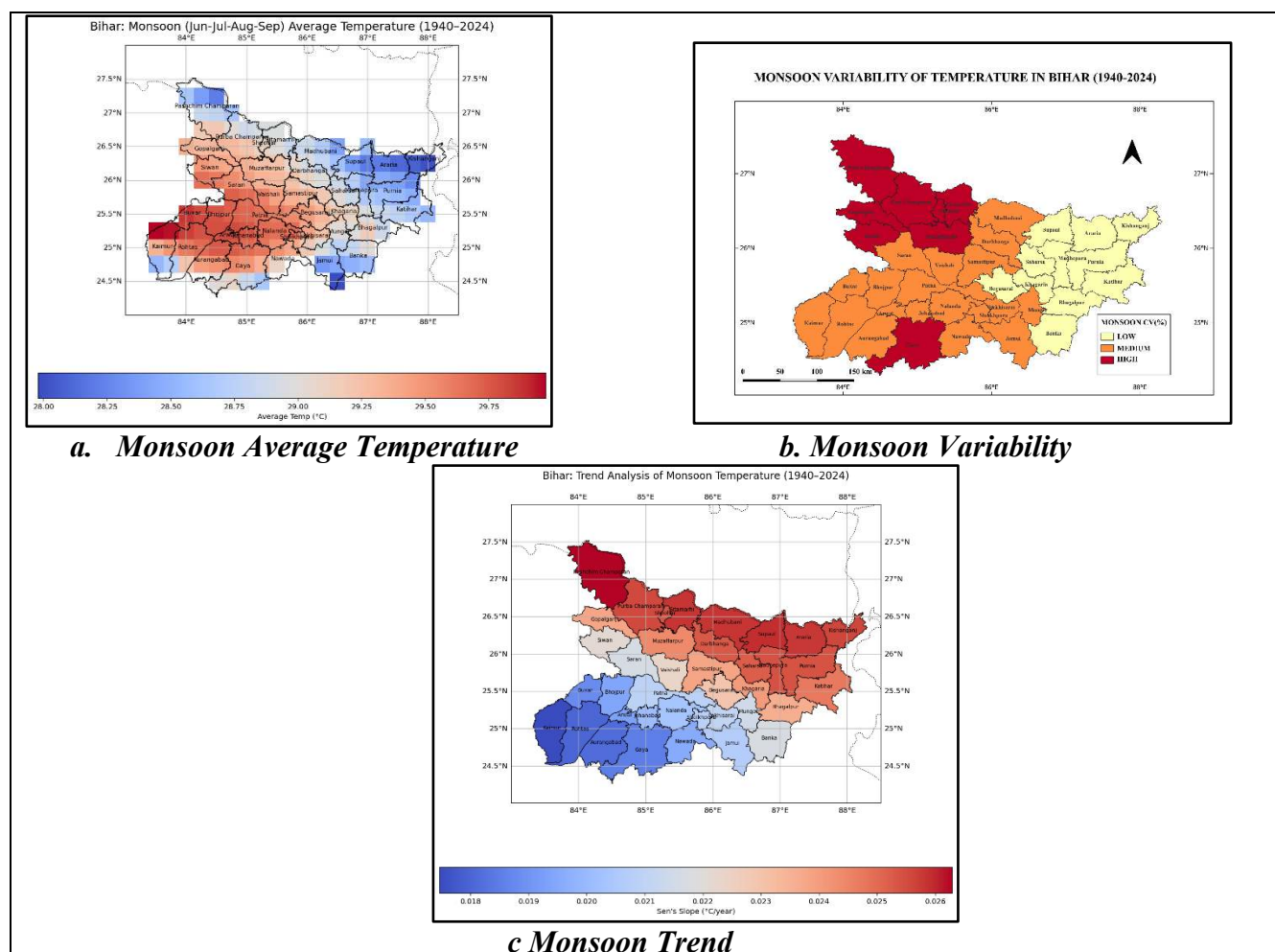


Fig 6: Monsoon Temperature Pattern, Variability, and Trend; Source: Prepared by authors

During the monsoon season (June–September), the highest mean temperatures are observed in south-western and central districts including Aurangabad, Arwal, Rohtas, Gaya, and Jehanabad, often exceeding 29.5°C. North-eastern districts such as Kishanganj, Araria, Purnia, and Supaul record mean temperatures below 28.5°C. Variability analysis reveals high temperature variability in northern districts, moderate variability in south-central and western districts, and lower variability in eastern and north-eastern Bihar. Gaya exhibits notably high variability relative to surrounding districts. Trend analysis indicates statistically significant

increasing trends across all 38 districts, with Sen's Slope values ranging from 0.02°C to 0.03°C per year.

5.5 Post-Monsoon Temperature Characteristics

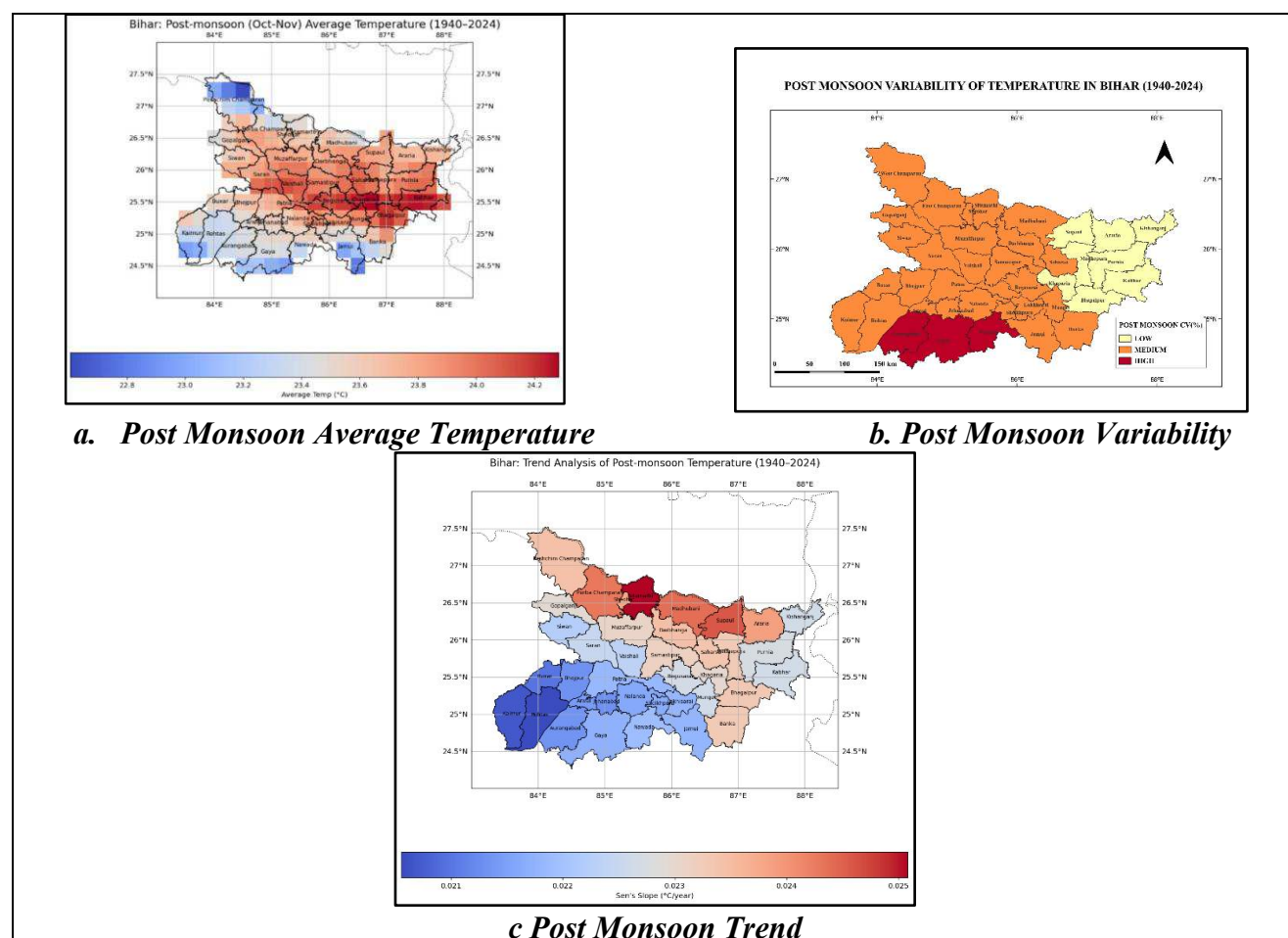


Fig 7: Post Monsoon Temperature Pattern, Variability, and Trend; Source: Prepared by authors

Post-monsoon (October–November) temperatures display a distinct spatial pattern across Bihar. Higher mean temperatures exceeding 24°C are recorded in north-eastern and eastern districts such as Katihar, Khagaria, Saharsa, Bhagalpur, and Purnia, while lower values are observed in south-western and southern districts including Jamui, Kaimur, Rohtas, and Aurangabad. Variability increases gradually from north-eastern to south-western districts, with Aurangabad, Gaya, and Nawada showing higher variability. Trend analysis reveals statistically significant increasing trends across all districts, with stronger signals in north-eastern and north-central Bihar. The cumulative rise in post-monsoon temperature is estimated at approximately 1.86°C over the study period.

5.6 Annual Precipitation Pattern, Variability, and Trends

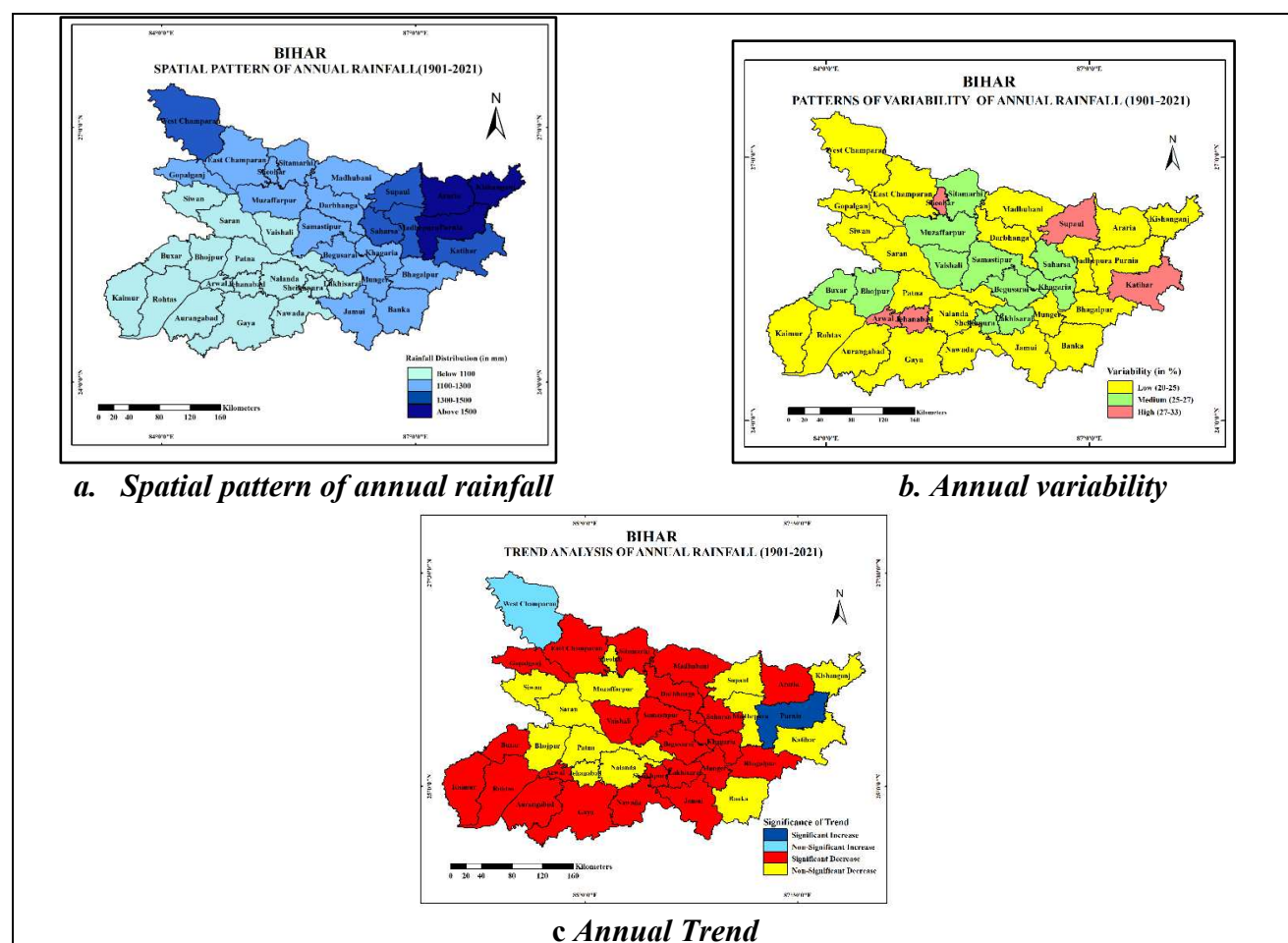
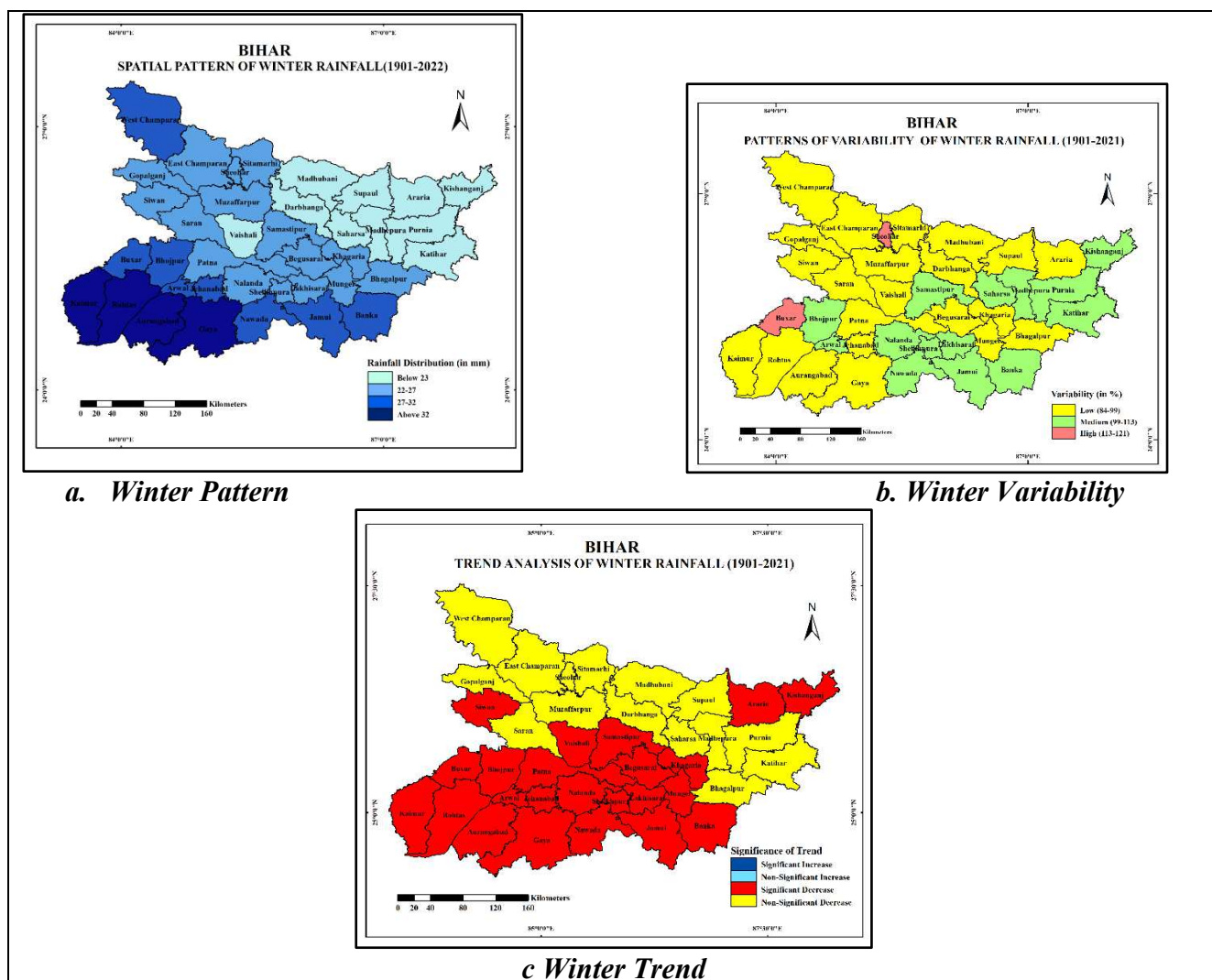


Fig 8: Annual Precipitation Pattern, Variability, and Trends; Source: Prepared by authors

Analysis of long-term annual precipitation across Bihar during 1901–2021 reveals pronounced spatial heterogeneity and substantial inter-annual variability. Mean annual rainfall exhibits a clear northeast–southwest gradient, with the highest values recorded in north-eastern districts such as Kishanganj, Araria, Purnia, and Katihar, while comparatively lower rainfall characterizes south-western districts including Buxar, Arwal, Bhojpur, and Rohtas. Across districts, annual rainfall shows wide dispersion, as reflected by high standard deviation and coefficient of variation values, indicating frequent departures from long-term means. Districts located within the Subtropical Monsoon (Cwa) climate zone record higher rainfall magnitude and variability compared to those in the Tropical Savanna (Aw) zone. Trend analysis indicates spatially mixed behaviour, with several districts exhibiting increasing trends, while others show weak or non-significant changes, highlighting the absence of a uniform long-term precipitation trend across the state.

294 5.7 Winter Precipitation Characteristics



295 **Fig 9: Winter Precipitation Pattern, Variability, and Trends; Source: Prepared by authors**

296 Winter precipitation (January–February) contributes a very small proportion to Bihar’s annual
 297 rainfall total but displays extremely high relative variability. Mean winter rainfall remains low
 298 across all districts, generally below 30 mm. Southern and south-central districts record
 299 relatively higher winter rainfall compared to northern districts, where precipitation is minimal.
 300 Variability measures reveal exceptionally high coefficients of variation and positively skewed
 301 distributions across the state, indicating that winter rainfall is episodic and concentrated in a
 302 few isolated events. Trend analysis shows largely non-significant trends in winter precipitation
 303 across most districts.

304

5.8 Pre-Monsoon Precipitation Characteristics

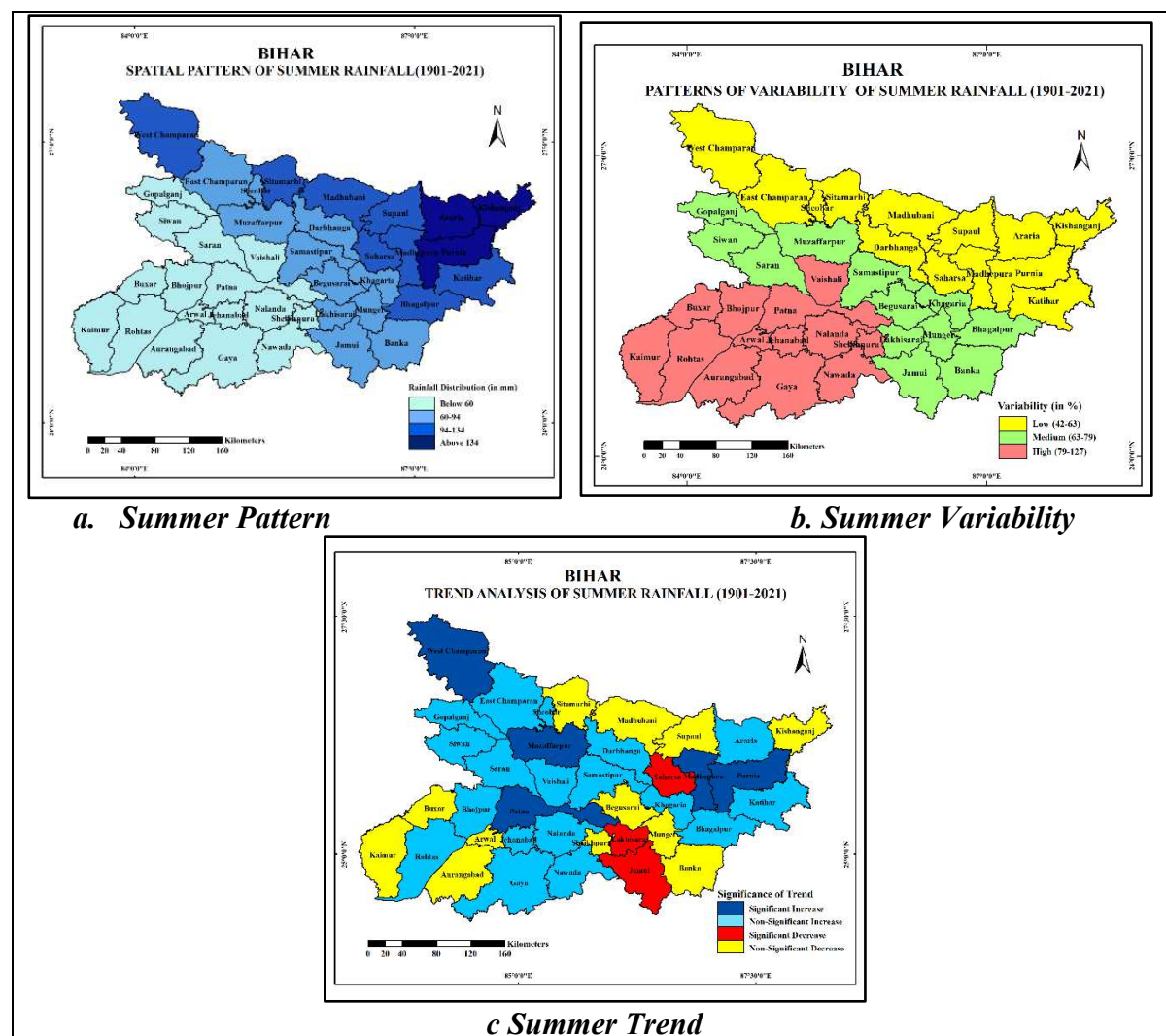


Fig 10: Pre-Monsoon Precipitation Pattern, Variability, and Trends; Source: Prepared by authors

Pre-monsoon rainfall (March-May) exhibits strong spatial contrasts and high variability across Bihar. North-eastern districts, including Kishanganj, Araria, Purnia, and Katihar, receive comparatively higher pre-monsoon rainfall, while western and south-western districts such as Kaimur, Buxar, Arwal, and Rohtas experience markedly lower amounts. CVs are high across most districts, reflecting the dominance of localized convective rainfall events. Several districts record high maximum rainfall values despite low seasonal means, indicating short-duration, high-intensity precipitation. Trend analysis reveals predominantly non-significant trends, suggesting limited long-term change in pre-monsoon rainfall.

5.9 Monsoon Precipitation Characteristics

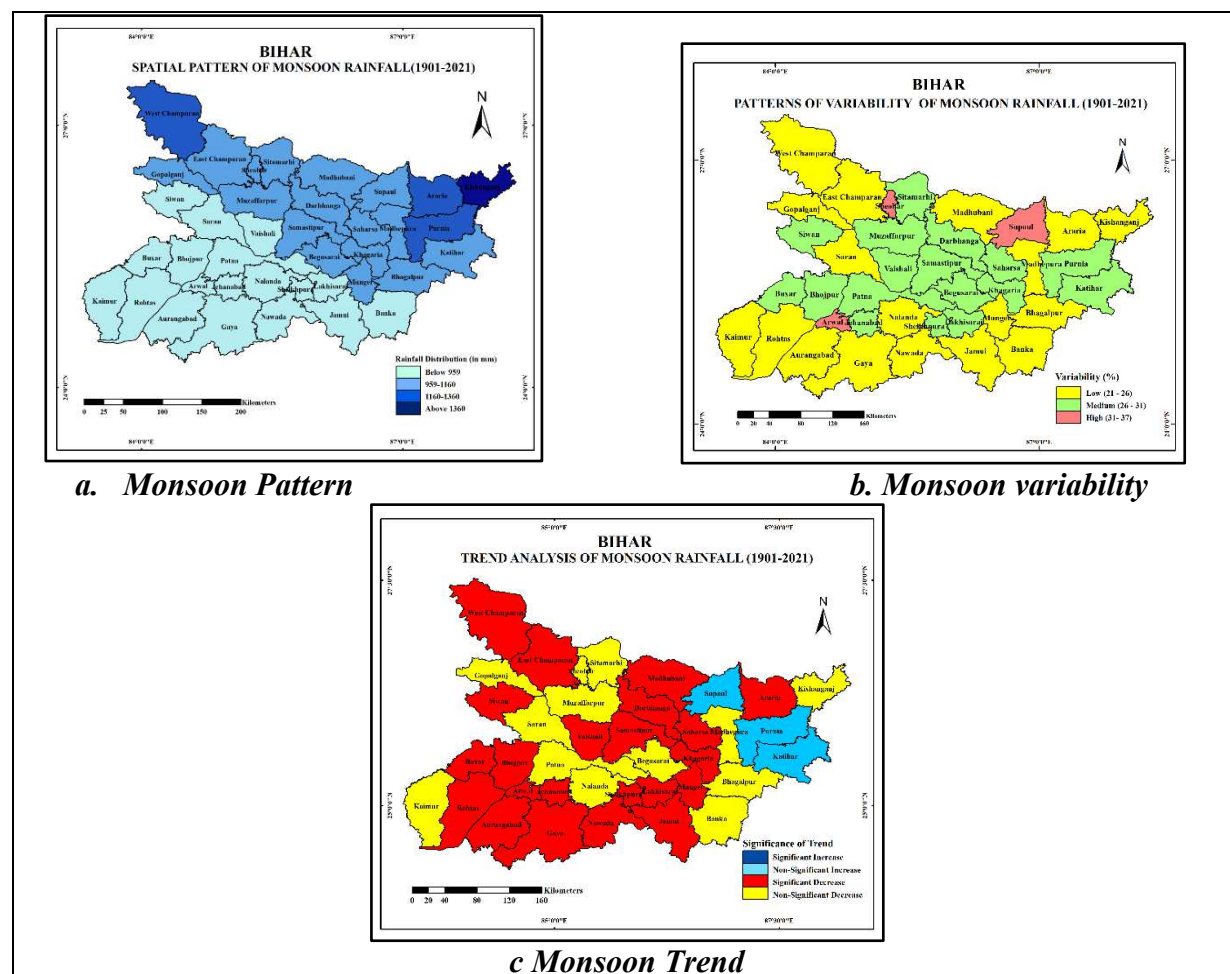


Fig 11: Monsoon Precipitation Pattern, Variability, and Trends; Source: Prepared by authors

The south-west monsoon season (June–September) accounts for the largest share of annual precipitation across Bihar. Eastern and north-eastern districts record the highest monsoon rainfall totals, with Kishanganj consistently receiving the maximum amounts, whereas southwestern districts such as Arwal, Buxar, Bhojpur, and Nalanda receive comparatively lower rainfall. Despite high mean monsoon rainfall, variability remains substantial across districts, with wide rainfall ranges indicating frequent occurrences of both excess and deficit years. Trend analysis reveals spatially heterogeneous behaviour, with some districts showing increasing monsoon rainfall and others exhibiting weak or non-significant trends.

5.10 Post-Monsoon Precipitation Characteristics

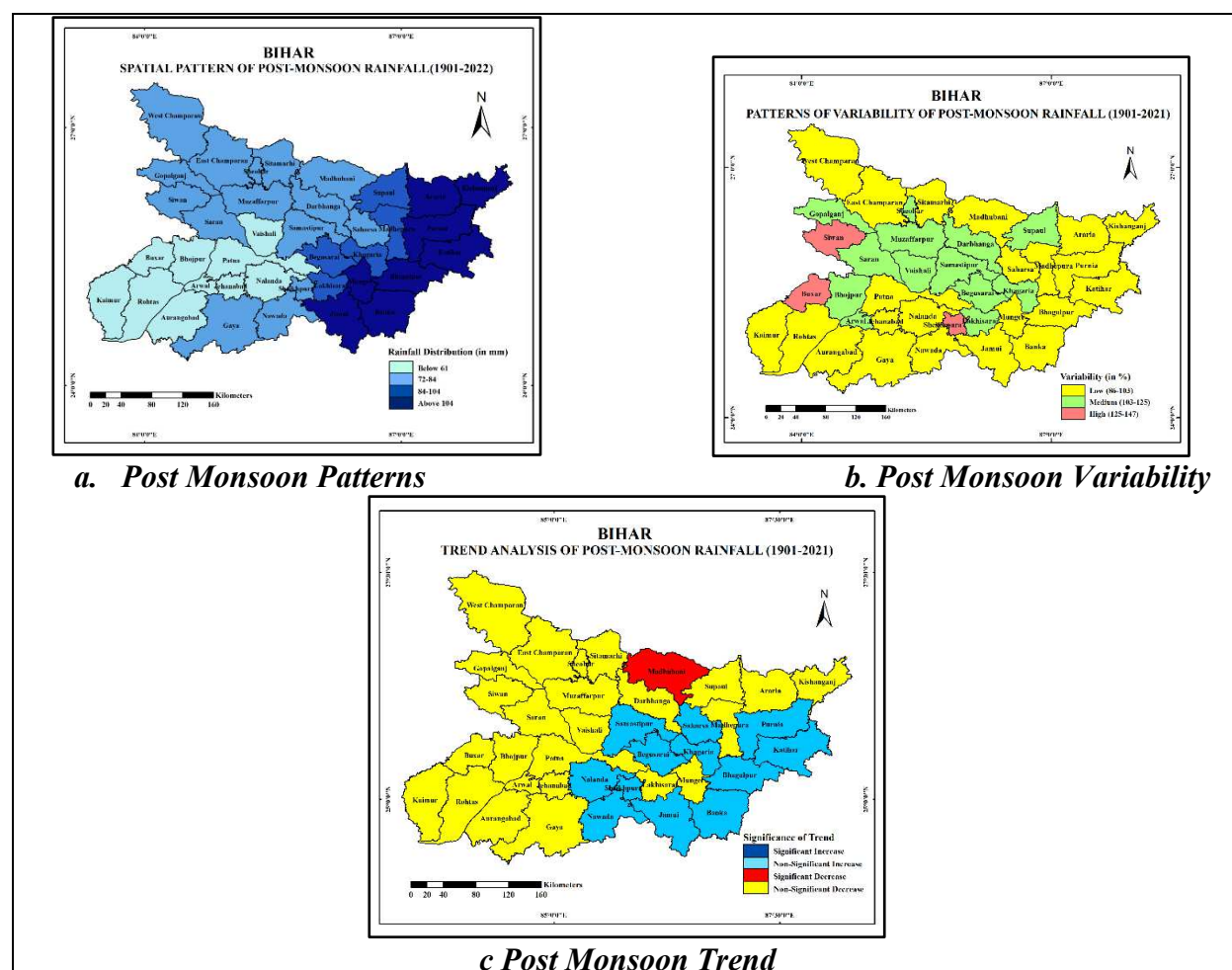


Fig 12: Post Monsoon Precipitation Pattern, Variability, and Trends; Source: Prepared by authors

Post-monsoon rainfall (October–December) is relatively low across Bihar and exhibits pronounced variability. Eastern districts, particularly Kishanganj, Araria, Katihar, and Purnia, receive comparatively higher post-monsoon rainfall, while southern and south-western districts record minimal precipitation. High coefficients of variation and wide rainfall ranges are observed across districts, reflecting the sporadic nature of post-monsoon rainfall. Several districts record extreme maximum rainfall values despite low mean totals. Trend analysis indicates predominantly non-significant trends across most districts.

6. Trends in Temperature and Precipitation Extremes

6.1 Temperature Extremes

A) Intensity Indices

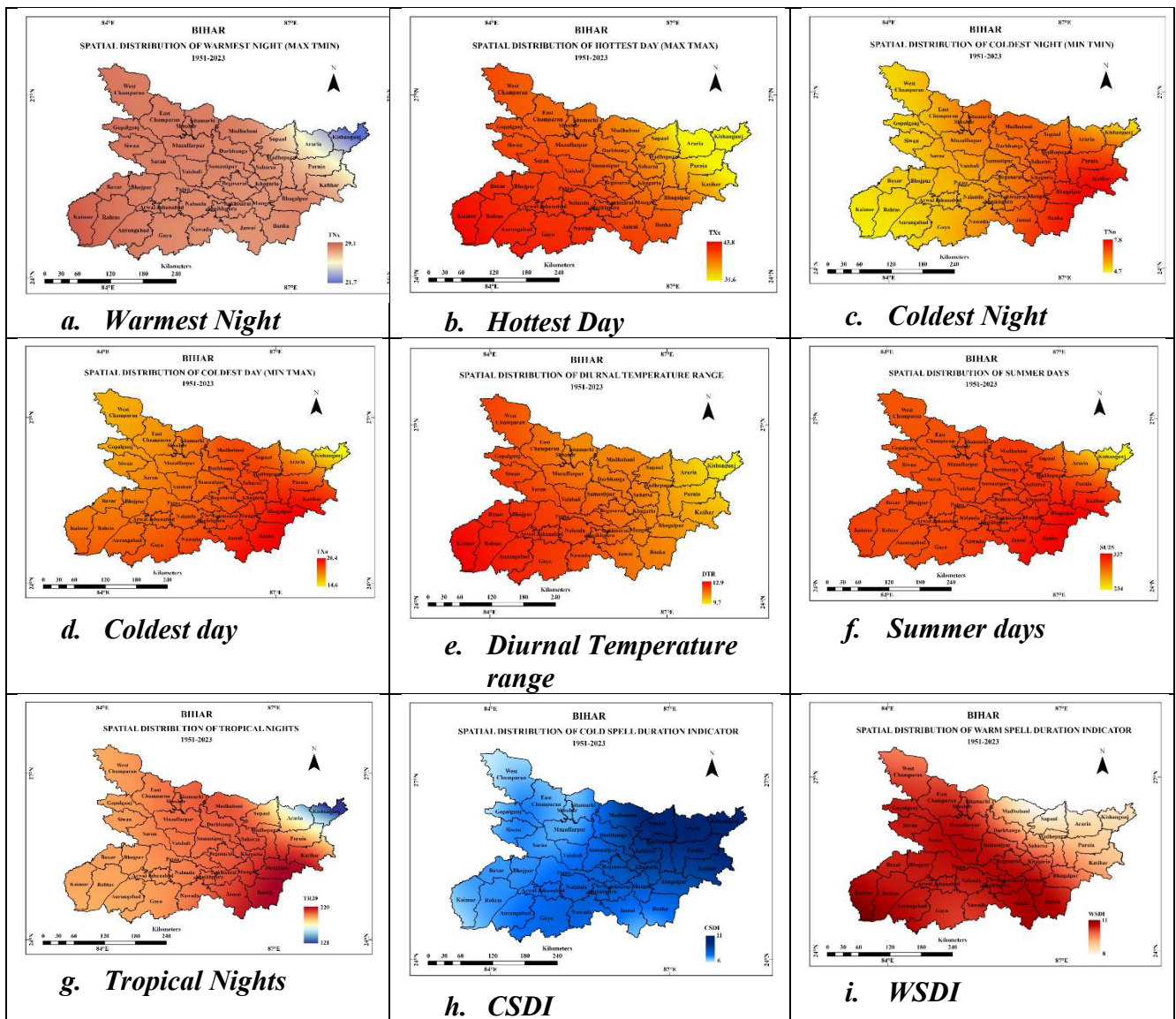
The spatial distribution of temperature extremes across Bihar reveals marked regional contrasts in both daytime and night-time conditions. The Warmest Night Temperature (TNx) exhibits a clear east–west gradient, with south-western Bihar recording the highest night-time maximum temperatures (often exceeding 28°C), while comparatively lower TNx values (below approximately 25°C) are observed in the eastern districts. Similarly, the Hottest Day Temperature (TXx) indicates that western and central Bihar experience the most intense daytime extremes, frequently surpassing 43°C, highlighting the pronounced heat stress conditions in these regions. In contrast, the Coldest Night Temperature (TNn) pattern shows that southern and western Bihar experience colder nights, whereas northern districts maintain relatively higher minimum temperatures. The Coldest Day Temperature (TXn) shows spatial variability, with northern and western districts with lower daytime minima (around 14°C), while central Bihar districts remain relatively warmer (approximately 20°C). The Diurnal Temperature Range (DTR) is notably higher in western Bihar due to stronger daytime heating and cooler nights, whereas eastern Bihar shows a comparatively narrower DTR, indicating moderated thermal contrasts between day and night.

B) Frequency Indices

The Summer Days index (SU25) indicates that central and southern Bihar experience more than 300 days annually with maximum temperatures exceeding 25°C, reflecting prolonged warm conditions throughout the year. In contrast, the Tropical Nights index (TR20) reveals fewer warm nights in north-eastern Bihar (less than 120 days annually), whereas central districts record more than 200 tropical nights per year, pointing to intensified night-time heat stress in these regions. The Cold Spell Duration Index (CSDI) shows that northern and north-eastern districts more commonly experience longer cold spells. However, trend analysis indicates a significant decline in cold-spell duration over time, consistent with warming winter conditions and reduced cold-event severity. Conversely, the Warm Spell Duration Index (WSDI) demonstrates that southern Bihar experiences relatively longer warm spells.

372 C) Percentile-Based Indices

373 The Cool Nights (TN10p) and Cool Days (TX10p) indices show the highest percentages in
 374 northern and north-eastern Bihar; in contrast, central and southern Bihar exhibit a reduced
 375 frequency of such cool extremes, reflecting the broader warming tendency observed over the
 376 recent decade. Conversely, the Warm Nights (TN90p) and Warm Days (TX90p) indices reveal
 377 a rising dominance of heat-related extremes. Southern and south-eastern Bihar record high
 378 frequencies of warm nights, while northern and central districts show elevated percentages of
 379 warm days. These patterns are consistent with broader continental-scale warming trends, where
 380 both extreme night-time and daytime temperatures are intensifying.



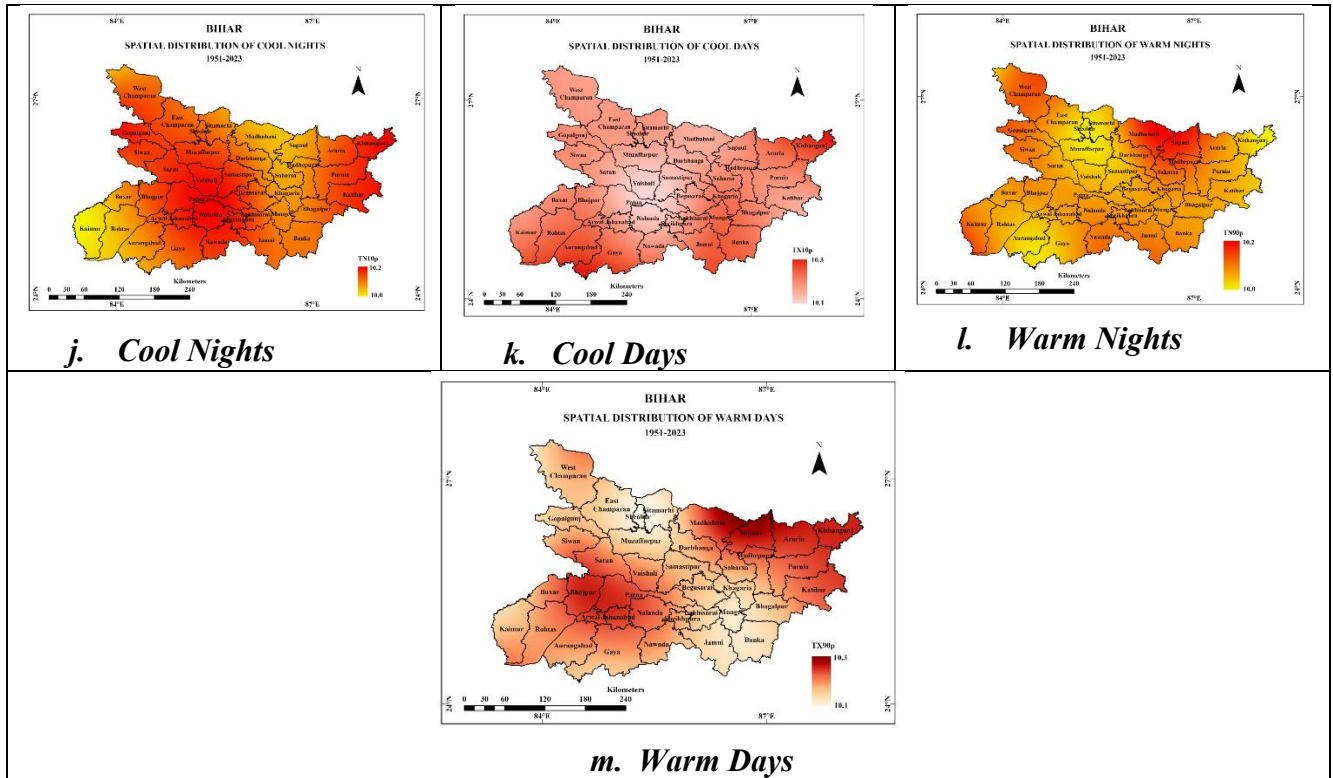


Fig 13: Temperature Extremes

6.3 Trends in Precipitation Extremes

The indices are grouped into frequency-based indices, which describe the occurrence of wet and dry spells, and intensity-based indices, which capture the magnitude of rainfall during extreme events.

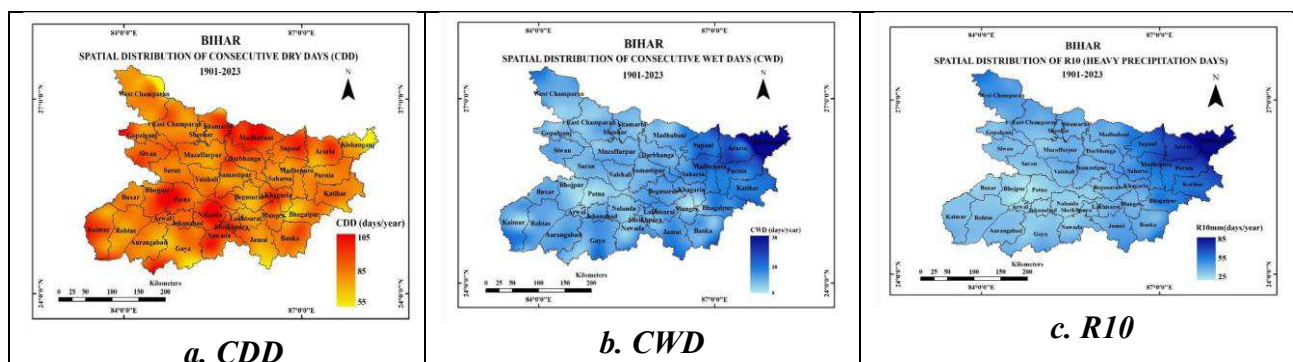
A) Frequency Indices

The spatial distribution of CDD shows pronounced drought-prone conditions in central and southern Bihar, where prolonged dry spells ranging from 85 to 105 days per year are observed. Districts such as Patna, Nalanda, Gaya, Nawada, Sheikhpura, Bhojpur, and Jehanabad show the highest CDD values, indicating increasingly persistent dry periods. In contrast, northern and northeastern districts including West Champaran, Muzaffarpur, Kishanganj, Araria, and Purnia record lower CDD values (55–85 days), reflecting relatively humid conditions and stronger monsoonal influence. North-eastern Bihar experiences the longest consecutive wet spells, with 28–38 wet days per year recorded in districts such as Kishanganj, Araria, Purnia, Katihar, Supaul, and Bhagalpur. In contrast, central and southern Bihar show shorter wet spells. R10 (>10 mm/day) shows the highest frequency (up to 85 days/year) in north-eastern Bihar,

while western and south-western districts record fewer than 35 days/year. R20 (>20 mm/day) further concentrates heavy rainfall in Kishanganj, Araria, Purnia, and Katihar, indicating heightened flood susceptibility. R25 (>25 mm/day) confirms that very heavy rainfall events are most frequent in north-eastern and eastern Bihar, whereas south-western districts such as Gaya, Rohtas, and Aurangabad experience the fewest such events.

B) Intensity Indices

Total annual precipitation (PRCPTOT) is highest in north-eastern districts, reaching up to 3400 mm per year, while central and western districts receive significantly lower totals (900–2100 mm). The strong spatial correspondence between high PRCPTOT and high CWD, and between low PRCPTOT and high CDD, highlights the uneven and regionally imbalanced rainfall distribution across the state. Despite substantial rainfall in the northeast, trend analysis indicates a significant decline in annual totals. The Simple Daily Intensity Index (SDII) further demonstrates that northern districts such as West Champaran, East Champaran, Kishanganj, and Araria experience high-intensity rainfall (20–25 mm/day), whereas southern districts record comparatively lower intensity (10–15 mm/day). RX1DAY values exceed 170 mm/day in northeastern districts such as Kishanganj, Purnia, and Araria, while RX5DAY totals reach 370–400 mm, indicating multi-day heavy rainfall episodes capable of triggering severe floods. Very Wet Days (R95p) and Extremely Wet Days (R99p) are heavily concentrated in north-eastern Bihar, with substantially lower contributions from extreme rainfall in western and south-western districts. Together, these patterns confirm a dual climatic vulnerability in Bihar—heightened flood risk in the northeast and increasing drought stress in the southwest—reflecting the growing variability and extremity of monsoon behaviour under ongoing climate change.



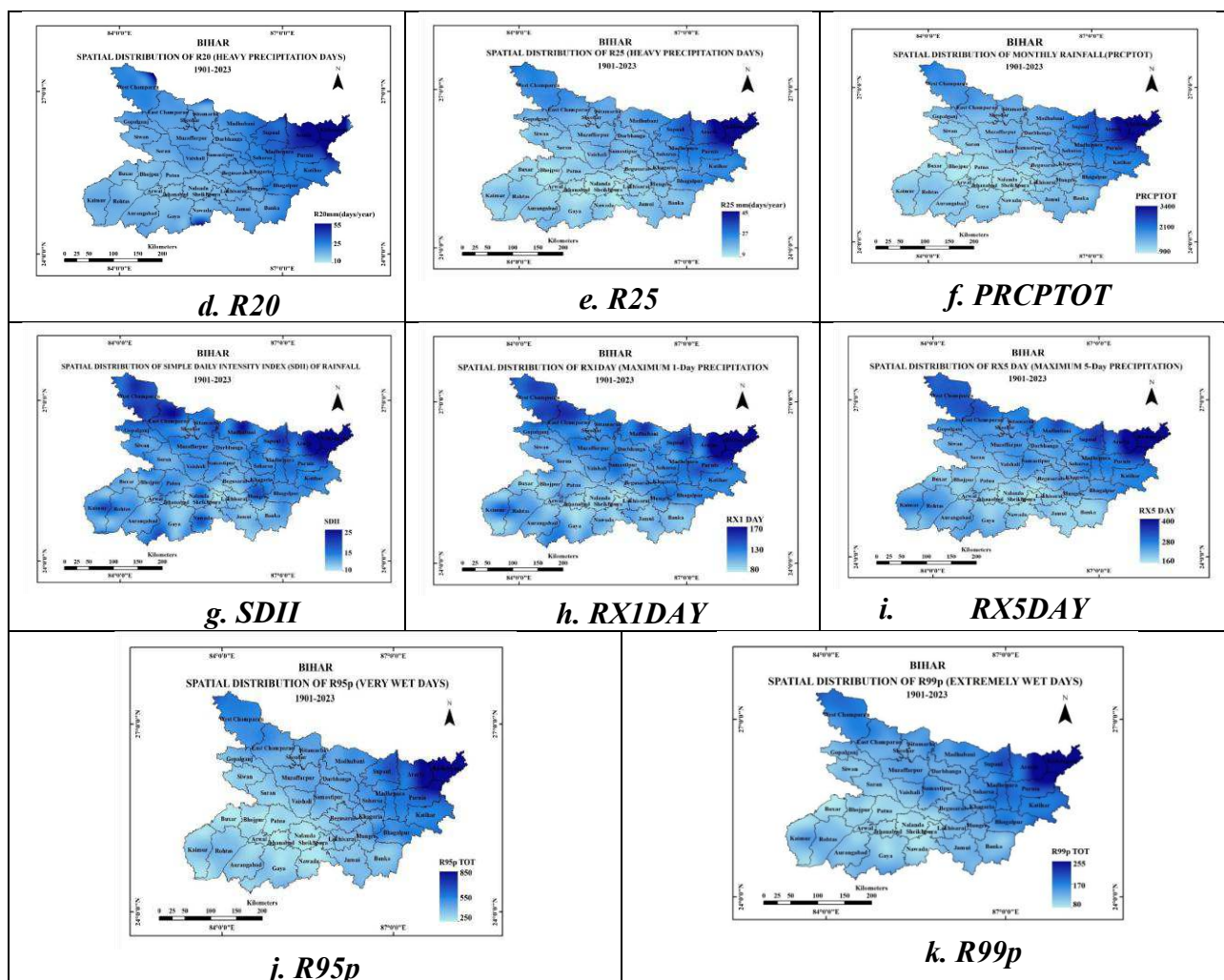


Fig 14: Precipitation Extremes

Overall, precipitation extremes in Bihar exhibit strong spatial asymmetry and increasing variability. North-eastern Bihar remains highly vulnerable to floods due to intense, frequent rainfall extremes, while central and south-western Bihar face escalating drought risk due to longer dry spells and declining rainfall totals. These findings underscore the urgent need for region-specific climate adaptation strategies that integrate flood control, drought-resilient agriculture, and improved water management systems.

7. Multidisciplinary Climate-Risk Assessment Framework

By operationalizing an integrated multidisciplinary climate-risk framework grounded in the IPCC risk paradigm ($Risk = Hazard * Exposure * Vulnerability$), this study demonstrates that hydro-climatic impacts across Bihar are co-produced by physical atmospheric drivers and localized socio-ecological precarity. Synthesizing over a century of meteorological

observations (1901-2024) with spatial demographic and ecological data reveals a severe hydro-climatic bifurcation: northern and northeastern districts (such as Sitamarhi, Madhubani, and Darbhanga) face escalating extreme precipitation events and recurrent inundation of floodplain ecosystems, whereas central and southwestern districts face accelerating thermal stress, rising monsoon minimum temperatures, and prolonged dry spells where Consecutive Dry Days (CDD) regularly exceed 85–105 days per year. These atmospheric hazards translate into severe systemic risks as they directly intersect with high population densities, smallholder agriculture, vulnerable physical infrastructure, and declining aquatic commons like *chaurs* and *mauns*. Because structural vulnerabilities including extreme land fragmentation, high reliance on rainfed farming, groundwater depletion, and unequal institutional access amplify physical exposure, climate risk functions not merely as an external physical shock, but as a socio-hydrological vulnerability. Consequently, addressing Bihar's complex risk profile requires shifting away from reactive, relief-dominated governance toward spatially differentiated, climate-resilient policy pathways: institutionalizing advanced flood early-warning networks, drainage optimization, and community-led wetland restoration in the waterlogged northeast, while simultaneously deploying drought-tolerant crop cultivars, solar-powered micro-irrigation, managed aquifer recharge, and localized Heat Action Plans (HAPs) across the heat- and drought-stressed central and southwestern belts.

8. Compound and interacting hazards, in which Interacting Climate Risks

Climate risks in Bihar should not be viewed separately because two or more hazards can occur together or one after another and may amplify their combined impacts. The present assessment of Bihar shows that two or more climate-related hazards can interact and produce greater impacts than each hazard alone.

One important compound risk is the interaction between heat and dry spells. High temperatures during prolonged rainfall deficits can increase evapotranspiration, reduce soil moisture, intensify crop water requirements, and increase thermal stress on agricultural systems and populations. This interaction is particularly important for central and south-western Bihar, where higher temperatures coincide with longer dry spells and comparatively lower rainfall. Another key hazard is extreme rainfall, and flooding is an important interacting hazard in north-eastern Bihar. High-intensity rainfall events combined with saturated soils, river overflow, inadequate drainage, and low-lying floodplains can rapidly increase flood severity. The concentration of high rainfall totals, intense rainfall indices, and wet spells in north-eastern

districts indicates the potential for recurrent compound flood events. Another key interaction is rainfall deficit and groundwater stress. Reduced rainfall can lower natural recharge while increasing dependence on groundwater for irrigation and domestic requirements. Where rainfall deficits persist over several seasons, excessive groundwater withdrawal may further increase water-resource vulnerability. This condition is seen in south Bihar, where heat and water scarcity create a reinforcing cycle in which rising temperatures increase water demand as availability declines.

Northeast Bihar faces flooding and water contamination, which occur together when floodwaters mix with wastewater, agricultural runoff, and other contaminants, affecting drinking-water sources and increasing risks to human health and livelihoods. Excess rainfall followed by dry conditions can cause waterlogging or flooding first and moisture shortages later, creating difficulties for crop growth, soil conditions, and water management. Bihar therefore needs an integrated approach that considers not only individual hazards but also their time period, spatial distribution, and combined effects. Including compound hazards in climate-risk assessments can improve early-warning systems, agricultural planning, disaster preparedness, and water-resource management.

9. Nature-Based Solutions and Ecosystem-Based Adaptation

Bihar has many rivers, wetlands, floodplains, ponds, agricultural areas, and groundwater-dependent ecosystems. Nature-based solutions and ecosystem-based adaptation can help reduce climate risks and strengthen ecological resilience. Bihar has many rivers, wetlands, floodplains, ponds, agricultural areas, and groundwater-dependent ecosystems, and restoring these natural resources can help reduce flood risk and manage drought and water shortages.

In north-eastern Bihar wetland restoration and floodplain conservation can form a central component of flood-risk management. Wetlands and functioning floodplains can temporarily store excess rainfall and floodwater, slow surface runoff, support groundwater recharge, and provide ecological habitats. Protecting natural floodplain areas can reduce flood risk to settlements and infrastructure. Pond restoration represents another locally appropriate adaptation measure. Traditional ponds and village water bodies can improve local water storage, support groundwater recharge, provide supplementary irrigation, and increase water availability during dry periods. Their protection is particularly beneficial in areas experiencing increasing rainfall variability and prolonged dry spells. Restoring traditional water-

management systems such as ahar-pyne networks can also provide an additional pathway for climate adaptation. These systems can make it easier to collect, store, and distribute monsoon water, supporting irrigation and reducing the impacts of excess surface runoff. Restoring these traditional systems combined with modern water-management practices can help reduce both flood and drought risks. Groundwater recharge can be improved through recharge structures, restoration of ponds and wetlands, and increasing areas where rainwater can seep into the ground. These measures can improve water availability, reduce dependence on groundwater during dry periods, and help store more rainwater. Riparian vegetation, afforestation, and agroforestry can also help control erosion, stabilize riverbanks, conserve soil, retain water, and reduce surface runoff. These measures can also provide shade and improve landscape resilience to heat and rainfall variability.

Overall, an ecosystem-based approach should not replace structural measures; rather, it should complement them through a hybrid climate-resilience strategy. Combining these approaches can reduce multiple climate risks while supporting agriculture, biodiversity, water security, and rural livelihoods. This integrated approach can help Bihar build a more climate-resilient and sustainable future.

10. Climate Vulnerability and Adaptive Capacity in Bihar

Bihar is shaped by dense settlement, agricultural dependence, its riverine location, concentrated infrastructure, and reliance on climate-sensitive natural resources. Sensitivity depends on landholding size, crop type, irrigation dependence, livelihood diversification, health conditions, housing quality, and access to essential services. Adaptive capacity depends on income, information, technology, institutional support, infrastructure, and the ability to modify livelihood or production practices. The State Action Plan on Climate Change for Bihar identifies agriculture, water resources, health, and livelihoods among the sectors particularly vulnerable to climate variability and change [8]. The broader national assessment of climate change in India similarly highlights these sectors' sensitivity to changing climatic conditions [14].

Exposure is particularly high in the northern floodplains. Dense settlements, productive agricultural land, roads, schools, and other infrastructure are located in areas influenced by rivers such as the Kosi, Gandak, Bagmati, and Burhi Gandak. Recurrent flooding affects agricultural land, housing, transport infrastructure, water supply, and other essential services. Recent research on flood-prone regions of eastern India indicates that recurrent flooding

contributes substantially to livelihood vulnerability and can influence migration as an adaptation strategy among farm households [20]. Small and marginal farmers are particularly sensitive because their livelihoods depend heavily on agricultural production and they generally possess fewer resources to recover from climate-related losses. A study of farmers in Zone-II of Bihar reported a vulnerability index of 0.41 for the Kosi region, indicating substantial vulnerability to climatic variability. The study further emphasized the importance of strengthening farmers' capacity to respond to climate-related risks through appropriate agricultural practices and improved production systems [19].

In drought-prone southern and central districts, sensitivity is expressed through dependence on groundwater and rain-fed agriculture. Excessive groundwater extraction to compensate for rainfall deficits can weaken the resource base. The importance of groundwater in sustaining agricultural and water requirements under changing monsoon conditions has been demonstrated for India [2]. Women and children may face disproportionate burdens when household water sources become unreliable. Health exposure is also uneven, with heat extremes particularly affecting vulnerable populations and outdoor workers. Flooding can contaminate drinking-water sources and increase exposure to water-related diseases. The State Action Plan on Climate Change and Human Health for Bihar recognizes climate-related health risks and the need for appropriate adaptation and preparedness measures [31]. More broadly, climate change is increasingly recognized as an important determinant of health through heat exposure, changing disease patterns, water insecurity, and disruption of health-related services [35]. The health dimension of climate vulnerability therefore requires adaptation measures that extend beyond physical infrastructure to include early-warning systems, public-health preparedness, access to safe drinking water, and targeted protection for vulnerable groups [31,35].

Migration represents another important dimension of climate vulnerability and adaptation in Bihar. For some rural households, temporary migration provides an alternative source of income when agricultural livelihoods are disrupted by floods or other climatic stresses. Recent evidence from flood-prone eastern India indicates that livelihood vulnerability and recurrent flooding are important factors associated with migration decisions among farm households [20]. Climate vulnerability therefore has a strong social dimension. Adaptive capacity is not evenly distributed within a district, and Bihar should consequently be treated as a mosaic of district- and sector-specific risk profiles rather than as a single homogeneous vulnerability zone. Adaptive capacity nevertheless exists and can be strengthened through appropriate

institutional, infrastructural, and community-level interventions. The study identifies three broad planning regions: the north and north-east flood–extreme-rainfall belt; the central transition belt, where both drought and flood risks can occur; and the south and south-west drought–heat belt.

Agriculture is the most directly exposed sector because crop calendars, yields, and farm incomes are closely connected to temperature and rainfall. Northern agriculture faces flooding, waterlogging, erosion, and crop loss, whereas central and southern agriculture faces delayed rainfall, dry spells, groundwater stress, and heat. Warmer conditions can shorten crop growth duration and affect temperature-sensitive crops such as wheat, while climate variability can increase production risks [26]. The appropriate adaptation response is therefore location-specific: flood-tolerant crops and improved drainage in flood-prone areas, drought-resilient varieties and water-saving irrigation in dry areas, and diversified farming systems in transition zones. Crop diversification, stress-tolerant varieties, irrigation improvements, insurance, and climate advisories can strengthen agricultural resilience. Community participation in plantation and ecosystem restoration can further support ecosystem services and climate adaptation, consistent with the objectives of Bihar’s climate-resilience initiatives [8,12].

Water resources experience a dual pressure. In the north, intense rainfall and flooding can create excess water, sedimentation, and contamination. In the south, prolonged dry periods and rainfall deficits increase dependence on groundwater. This means that water-security policy should move beyond a simple supply-expansion approach towards integrated management of rainfall, surface water, groundwater, storage, recharge, and demand. The relationship between monsoon precipitation, groundwater pumping, and changes in groundwater storage demonstrates the importance of integrated water-resource management in India [2]. Floodwater may therefore be treated partly as a resource for managed recharge and local storage where technically feasible, while drought planning should emphasize demand management and quifer protection.

Health vulnerability is closely linked to heat- and water-related stresses. Heat-action plans, early-warning systems, and strengthened health infrastructure are relevant to districts exposed to extreme temperatures. Flood preparedness must include safe drinking water, sanitation, disease surveillance, and continuity of essential health services. Climate change can increase health risks through heat stress, shifting vector ecology, water contamination, and disruptions

to sanitation and water systems [35,36]. These risks highlight the need for integrated climate-health planning at the state and district levels [31].

Infrastructure vulnerability includes roads, bridges, schools, health facilities, drainage systems, and flood-control structures. Evidence on natural hazards in Bihar shows the importance of considering multiple interacting hazards in infrastructure and spatial planning [7,38]. Protective infrastructure can reduce one risk while unintentionally increasing another if it does not adequately account for drainage and downstream consequences. Future infrastructure should therefore be designed using district-level climate extremes and changing hazard characteristics, not historical averages alone. The growing significance of hydro-climatic extremes under a changing climate further supports incorporating extreme-event information into infrastructure planning [5,24].

Ecosystems provide a further layer of adaptive capacity. Forests, wetlands, and protected areas regulate water, store carbon, support biodiversity, and provide livelihood services. Bihar's climate and environmental policy framework emphasizes ecosystem conservation and sustainable resource management as components of climate resilience [8,12]. Ecosystem restoration should therefore be considered both an adaptation investment and a conservation objective.

The analytical priority is therefore not to portray Bihar as lacking resilience, but to identify where existing adaptive capacity is insufficient relative to the speed, intensity, and spatial concentration of emerging climate risks. A differentiated approach that integrates climate information, sector-specific vulnerability, ecosystem-based adaptation, resilient infrastructure, and local institutional capacity is essential to strengthen Bihar's long-term climate resilience.

11. Existing climate adaptation and mitigation responses in Bihar

Bihar is highly vulnerable to climate variability because it depends on monsoon rainfall, so the state's climate response has evolved around both adaptation to climate-related hazards and mitigation of greenhouse-gas emissions. The Government of Bihar's climate framework combines sectoral interventions in water resources, agriculture, forestry, disaster management, energy and urban development. Bihar prepared its first State Action Plan on Climate Change in 2012 and adopted it in 2015, covering agriculture, water, forestry, energy, health, urban development and disaster management, while the Ministry of Environment, Forest and Climate Change currently lists the state's SAPCC 2.0 as under preparation.

One of Bihar's most important adaptation initiatives is the Jal-Jeevan-Hariyali Abhiyan (JJHA), launched in October 2019 to address environmental degradation, water scarcity, and the impacts of weather and climate extremes. Under the programme, Bihar has restored ponds, ahar-pynes, wells, and other water bodies; constructed check dams and water-harvesting structures; and carried out plantation activities. The state's Green Budget reported that thousands of water-resource schemes had been completed, restoring substantial irrigation and water-storage capacity. Water-resource management and irrigation development constitute another major component of Bihar's adaptation response. The state has promoted the renovation of traditional ahar-pyne systems, ponds and reservoirs, the construction of check dams and weirs, groundwater recharge, and the expansion of irrigation under initiatives such as *Har Khet Ko Pani*. According to the Bihar Green Budget, more than 2,100 ahar-pyne, weir, lift-irrigation, garland-trench and pond schemes had been completed, helping restore irrigation over approximately 2.41 lakh hectares and substantial water-storage. Mukhyamantri Khet Talab Yojana supports farm ponds in drought-prone areas. Such measures can reduce exposure if implemented with attention to hydrological conditions and maintenance. Bihar has promoted plantation through the Jal-Jeevan-Hariyali Abhiyan, MGNREGA and the Forest Department, with the objective of increasing tree and green cover.

In agriculture, the Bihar Kosi Basin Development Project offers a key example of adaptation. The project covers Araria, Madhepura, Purnia, Saharsa and Supaul and combines flood-management capacity with agricultural productivity, rural connectivity, institutional strengthening and climate-resilient agricultural practices. Research and wider adoption of Swarna Sub-1, a submergence-tolerant rice variety, has been documented in Sitamarhi, Darbhanga and Madhubani. The variety can tolerate submergence for approximately 12–15 days, making it particularly relevant to recurrent flash-flood conditions. ICAR identifies both flash floods/submergence and drought as major constraints to rice production in Bihar and recommends drought-tolerant varieties such as Vandana, Tulasi and Rajashree for appropriate upland conditions, while flood-prone areas require suitable flood/submergence-tolerant varieties. In 2024, the Government of India also released CR Dhan 108, a drought-tolerant rice variety specifically identified as useful for drought-prone conditions in Bihar. In districts such as Kishanganj, Araria, Purnia, Katihar, Supaul, Saharsa, Darbhanga, Sitamarhi and Madhubani, adaptation should increasingly combine flood forecasting and physical risk reduction with flood-resilient cropping systems.

The second major adaptation priority emerges from the study's evidence of increasing dry-spell persistence. Consecutive Dry Days (CDD) range from approximately 85–105 days per year in several central and southern districts where the highest values are reported for Patna, Nalanda, Gaya, Nawada, Sheikhpura, Bhojpur and Jehanabad. The study shows that central and western districts receive substantially lower annual precipitation (900–2100 mm). Consequently, adaptation in districts such as Gaya, Nawada, Nalanda, Patna, Sheikhpura, Jehanabad, Bhojpur, Arwal, Aurangabad and Rohtas need to emphasize on rainwater harvesting, farm ponds, groundwater recharge, micro-irrigation, water-use efficiency, drought-tolerant crops and crop diversification. Disaster-risk responses include early warning systems, flood management, heat action plans and communication strategies. The supplied material notes the use of locally accessible communication, including drum-based announcements in villages with limited digital access. This matters because early warning is effective only when information reaches people in an understandable form and is linked to a feasible protective action.

Bihar has also increasingly mainstreamed climate considerations into public finance through green budgeting. The state began its green-budgeting process in 2020–21, making Bihar one of the first Indian states to systematically identify and track environmentally oriented expenditure. The 2024–25 Green Budget further identifies a proposed “Climate Resilient and Low Carbon Development Pathway”, linking state development with the long-term objective of achieving net-zero emissions by 2070. Mitigation is increasingly connected with the Renewable Energy Policy 2025. The policy targets approximately 23.968 GW of renewable-energy capacity and 6.1 GWh of storage by 2029–30, with an emphasis on solar, biomass, waste-to-energy, and emerging technologies. In parallel, the state is promoting rooftop solar and solarisation of public infrastructure, thereby encouraging decentralised renewable-energy generation. The policy architecture therefore contains many of the necessary building blocks. The main challenge is to connect these initiatives to the observed spatial risk pattern. Adaptation should be prioritized where exposure and vulnerability are greatest, while mitigation should be designed so that it also generates local development benefits such as reliable energy, lower irrigation costs, and improved livelihoods and reduced pollution.

12. Institutional and policy gaps assessment

Policies exist but are not implemented effectively because of financial, institutional, technical, infrastructural, and awareness barriers. Climate action involves multiple departments, including agriculture, water, health, energy, forestry and disaster management, yet

coordination remains a continuing challenge. Without clear responsibilities, shared data systems and common indicators, programmes can become fragmented or duplicate effort.

Finance is another major constraint. The scale of investment required for climate-resilient irrigation, flood management, resilient infrastructure, renewable energy, health preparedness, and ecosystem restoration exceeds what routine departmental allocations can comfortably support. The SAPCC therefore requires a stronger pipeline of bankable projects and greater use of climate finance, blended finance and public-private partnerships where appropriate. Localized data remains a critical gap. State-level assessments can conceal substantial district differences. The supplied recommendations call for expanded automatic weather stations, river gauges and soil monitoring, collaboration with research institutions, open-access climate information and regular localized assessments. Such infrastructure would improve both early warning and long-term planning. Technical capacity is uneven. District and line-department officials require specialist support to interpret climate indices, projections, vulnerability assessments and cost-benefit information. Climate cells within agriculture, water and health departments, supported by technical institutions, could provide continuity and expertise. A high-level interdepartmental coordination mechanism could help align priorities and reduce institutional fragmentation.

Social communication is another policy gap. Climate information must be translated into locally meaningful decisions. Farmers need actionable crop and weather advisories, households need heat and flood warnings linked to protective behaviour, local governments need accessible risk maps and infrastructure standards. Awareness programmes should use local languages and culturally appropriate communication rather than relying only on technical reports. Traditional methods, such as using *nagada* (drum announcements) for heat warnings and local knowledge about seasonal changes, can be combined with modern tools like mobile apps and WhatsApp messages. This can make climate information more trusted and easier to reach people. Community-based organizations (CBOs), self-help groups (SHGs), and youth clubs should play an active role in local climate adaptation. Monitoring and evaluation must also improve. The supplied policy review recommends measurable indicators, baseline data, defined targets, independent evaluation, continuous learning and adaptive management. This is essential because climate conditions are changing and interventions may need to be modified. A climate-resilient policy system should therefore be iterative: observe, assess, implement, monitor, evaluate and revise.

13. Climate-resilient adaptation and mitigation pathways

The study's analysis supports a shift from hazard-specific projects to a district-sensitive, climate-resilient development framework. The central principle should be to integrate adaptation and mitigation with development planning rather than treat them as separate environmental activities. Climate risk should be incorporated into agriculture plans, water budgets, health systems, urban planning, infrastructure design, energy investments and local development programmes. For north-eastern flood-prone districts, the pathway should combine improved flood forecasting, last-mile early warning, resilient evacuation infrastructure, drainage improvement, flood-tolerant crops, raised storage, safe drinking-water systems, wetland restoration and risk-sensitive settlement planning. Assess embankments alongside drainage and floodplain processes rather than as stand-alone structures. Local water retention and wetland restoration can complement structural flood management.

For central districts, the priority should be flexible water management and compound-risk preparedness. These areas can experience both heavy rainfall and prolonged dry spells, while also facing significant heat stress. Farm ponds, rainwater harvesting, recharge structures, efficient irrigation, crop diversification, heat advisories and drainage improvement should be combined. District plans should explicitly consider the possibility of consecutive hazards within the same agricultural year. For southern and south-western districts, drought and heat resilience should dominate adaptation planning. Water-demand management, groundwater monitoring, micro-irrigation, drought-resilient crops, short-duration varieties, soil-moisture conservation and decentralized storage should be prioritized. Heat action plans should protect outdoor workers and vulnerable groups, while urban and peri-urban areas should expand shade, cool surfaces, water access and green infrastructure.

Agricultural adaptation should move toward climate-smart diversification. Flood-tolerant rice, drought-resistant pulses, millets, oilseeds, heat-resilient maize and short-duration varieties can reduce dependence on a single climatic window. Climate advisories should be integrated into extension services so that farmers receive information before sowing, irrigation and harvest decisions. Insurance and social protection should complement, rather than replace, physical and agronomic adaptation. Water-resilient development requires a basin-to-village continuum. District water plans should connect rainfall variability, surface-water storage, groundwater recharge, and irrigation demand and drinking-water security. In flood-prone areas, manage seasonal excess water through wetlands, ponds, and floodplain-compatible land uses where feasible. In drought-prone areas, combine recharge with abstraction controls and efficient

irrigation so conservation gains are not cancelled by rising demand. Mitigation should focus on development pathways with coupled benefits. The renewable-energy target provides a basis for expanding solar power, distributed generation, solar irrigation, storage, biomass and waste-to-energy. Energy efficiency in public buildings, schools, health facilities and irrigation systems can reduce emissions while lowering operating costs. Electric mobility and charging infrastructure can support cleaner urban systems when backed by reliable electricity. Ecosystem-based adaptation should be treated as core infrastructure. Forest restoration, wetland protection, agroforestry, riverine vegetation and biodiversity conservation can reduce heat, improve water regulation, store carbon and support livelihoods. Community participation is particularly important because long-term maintenance of ecosystem interventions depends on local institutions and incentives.

Finally, Bihar needs an implementation architecture that works climate science into district decisions. Climate cells should be established within key departments, supported by a state climate knowledge hub. District climate-risk profiles should be updated periodically using standardized indicators. Climate budgeting should identify adaptation and mitigation expenditure, while project estimation should include climate-risk screening. Public reporting should track outcomes, not just expenditure. This approach is consistent with the evidence in the supplied studies and provides a practical bridge between climate diagnostics and resilient development.

14. Discussion

The study draws on more than a century of precipitation information and several decades of temperature observations, placing both within a district-level spatial framework. The analysis therefore shows that Bihar cannot be represented by a single state-wide climate signal. Instead, it contains a pronounced spatial contrast between wetter, flood-exposed north-eastern districts and drier, drought-sensitive central and south-western districts. The temperature observations show northern and north-eastern districts such as Kishanganj, West Champaran, Supaul and Araria have comparatively lower annual mean temperatures, whereas south-central and south-western districts like Arwal, Aurangabad, Bhojpur, Rohtas, Gaya and Patna record higher values. Mean annual temperature ranges from approximately 24.59°C to 25.77°C, while coefficients of variation remain relatively low. At the same time, trend analysis identifies statistically significant warming in 33 of the 38 districts, with an overall increase of about 0.8–1.2°C and accelerated warming after the 1980s. The monsoon season shows particularly consistent warming, with significant positive trends across all 38 districts and Sen's slopes of

approximately 0.02–0.03°C per year. Precipitation observations show a strong northeast–southwest gradient in annual rainfall. Kishanganj, Araria, Purnia and Katihar receive the highest long-term rainfall, whereas Buxar, Arwal, Bhojpur and Rohtas are among the relatively drier districts. The evidence does not show uniform trend across the state rather than several districts show declining or weak trends while others show different behaviour.

Pre-monsoon temperatures are highest in central and south-western districts, with Aurangabad, Arwal and Rohtas approaching or exceeding 29.8°C in the seasonal mean. Gaya, Aurangabad and Rohtas also show large seasonal temperature ranges. During the monsoon, south-western and central districts remain warmer than the north-east, while the entire state shows statistically significant warming. Post-monsoon temperatures have increased across districts, with a reported cumulative rise of approximately 1.86°C over the study period. Winter behaviour is more heterogeneous, including decreasing trends in several southern and south-western districts, but this does not change the overall trend of long-term warming and declining cold extremes.

Winter rainfall is highly variable. Pre-monsoon rainfall is spatially uneven and frequently associated with localized convective events. The monsoon contributes the dominant share of annual rainfall and therefore controls the timing of sowing, irrigation demand, crop growth and flood exposure. Post-monsoon rainfall is comparatively low but irregular. These seasonal characteristics mean that a change in rainfall distribution can have a much larger practical effect than a similar change in the annual total. The study reports a statistically significant upward trend in Consecutive Dry Days, with Z approximately 2.07 and Sen's slope approximately +0.18 days per year. Central and southern districts frequently experience 85–105 dry days annually. At the same time, north-eastern districts exhibit intense rainfall characteristics, including high R10, R20 and R25 frequencies, high SDII, RX1DAY values exceeding 170 mm in some districts and RX5DAY totals around 370–400 mm. Thus, the climate signal is not simply 'more rain' or 'less rain'; it is a redistribution toward greater temporal unevenness. The extreme-event evidence establishes a clear geography of risk. Northern and north-eastern Bihar form the principal heavy-rainfall and flood hotspot, while central and south-western Bihar form the principal dry-spell and drought hotspot. Heat risk cuts across these zones, with the strongest daytime thermal extremes concentrated in western and central districts and substantial nighttime heat in southern and south-eastern areas.

Temperature extremes demonstrate a transition toward a heat-dominated regime. Hottest-day temperatures frequently exceed 43°C in western and central Bihar. Tropical nights are

substantially more common in central districts, where more than 200 such nights per year are reported in the study. Central and southern districts experience more than 300 summer days annually under the SU25 definition used in the analysis. Warm-day and warm-night percentile indices are increasingly dominant, while cool-day and cool-night frequencies decline. The Cold Spell Duration Index also shows a reduction in cold-spell duration, consistent with a shift toward warmer conditions.

Rainfall extremes produce an equally strong spatial asymmetry. North-eastern districts such as Kishanganj, Araria, Purnia and Katihar have high frequencies of heavy and very heavy rainfall. R10 can reach about 85 days per year, while R20 and R25 are concentrated in the same broad region. R95p and R99p contributions are also strongly concentrated in north-eastern Bihar. By contrast, Patna, Nalanda, Gaya, Nawada, Sheikhpura, Bhojpur, and Jehanabad show high CDD values. The prolonged dry-spell signal indicates drought and groundwater stress rather than merely low seasonal rainfall. Southern districts such as Gaya, Rohtas and Aurangabad also record fewer very heavy rainfall events, increasing dependence on water storage and irrigation. Central Bihar acts as an important transition zone because it can experience both excess-water and deficit-water conditions in different years.

14. Conclusion

Bihar is undergoing a measurable transition toward a warmer and more hydro-climatically variable regime. The strongest evidence is not a single change in annual rainfall but the interaction of warming, longer dry spells, intense short-duration rainfall and spatially concentrated extremes. Temperature trends are widespread, while precipitation changes are heterogeneous. This creates a dual-risk geography in which north-eastern districts are highly exposed to flooding and extreme rainfall, southern and south-western districts face drought and groundwater stress, and central districts may experience both risks alongside substantial heat exposure. Vulnerability depends on more than the physical hazard. Dense settlement, agricultural dependence, small landholdings, limited irrigation, livelihood insecurity, infrastructure deficits and unequal access to information shape sensitivity and adaptive capacity. Existing responses show that Bihar already has significant institutional and community capacity, but implementation needs to be more spatially targeted, better financed, more data-driven, and more accountable. The proposed framework therefore moves from observation to action: long-term climate monitoring should identify emerging variability; extreme-event analysis should define hotspots; exposure and adaptive-capacity assessment should identify who and what is at risk; district and sectorial vulnerability profiles should guide

investment; existing programmes should be aligned with observed risks; policy gaps should be addressed through stronger institutions, finance and knowledge systems; and adaptation and mitigation should be implemented as mutually reinforcing components of development planning. Such an approach can help Bihar move from reactive disaster response toward anticipatory, locally grounded and climate-resilient development.

Data Availability and Limitations:

The study uses IMD observational datasets, ERA-based reanalysis products, and freely available Terra-MODIS and Landsat data from USGS. IMD data are subject to the agency's data-access restrictions and may be obtained from the authors upon reasonable request, subject to IMD permission. Standard quality-control procedures were applied to improve data consistency and reliability

Acknowledgments:

The authors acknowledge the Advanced Research Centre Lab at L. N. Mithila University, Darbhanga, India; the Meteorological Department, Pune; the United States Geological Survey (USGS); and European Centre for Medium-Range Weather Forecasts (ECMWF) Reanalysis (ERA) for conducting the technical work for this research. We also acknowledge online research platforms such as ResearchGate and Google Scholar, which helped develop the framework for this study.

Contributions:

In this study, two authors have contributed as follows: study design: 1st author (Manu Raj Sharma) and 2nd author (Sukeshi Priya); Data collection: 1st author; analysis and interpretation of results: 1st and 2nd authors; draft manuscript preparation: 2nd author; reviewed and approved the final version of the manuscript: 1st and 2nd authors.

Conflict of Interest:

The authors have not declared any conflict of interest.

Clinical trial number:

Not applicable.

Ethics, Consent to Participate, and Consent to Publish declarations:

Not applicable

Funding:

The authors received no funds or financial assistance for this work.

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