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Research Paper

**SPATIAL RAINFALL VARIABILITY IN NORTH INDIA AND ITS
IMPLICATIONS FOR AGRICULTURE**

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Abstract

Rainfall is one of the most critical climatic parameters influencing agriculture, water resources, and socio-economic conditions in India. North India, comprising the states of Uttar Pradesh, Uttarakhand, Punjab, Haryana, Himachal Pradesh, Rajasthan, Delhi, Jammu & Kashmir, and parts of Bihar, is heavily dependent on the southwest monsoon. Any variation in rainfall distribution and amount has direct impacts on crop production, groundwater recharge, hydropower generation, and urban water supply. Rainfall variability in this region has increased in recent decades due to climate change and anthropogenic pressures. While some areas face recurrent droughts, others experience intense rainfall leading to floods. This study aims to assess rainfall variability in North India using secondary data from the India Meteorological Department (IMD) to analyze temporal trends and spatial variations over the last four decades. Findings highlight significant spatial heterogeneity. Mountain states such as Himachal Pradesh, Uttarakhand, and Jammu & Kashmir record high annual rainfall with moderate variability, supporting river recharge and hydropower potential. Arid and semi-arid states, particularly Rajasthan and Haryana, display low rainfall and high variability, making them highly drought-prone. Punjab and Uttar Pradesh, key Green Revolution states, receive moderate rainfall but show fluctuations that increase irrigation demand and groundwater stress. Bihar records high rainfall yet exhibits erratic patterns, rendering it simultaneously flood- and drought-prone. These disparities have profound implications. High variability undermines rainfed agriculture, compels groundwater over-extraction in irrigated zones, and heightens vulnerability to both droughts and floods. Consequently, agricultural stability and water security depend on effective adaptation measures. Suggested strategies include diversification to climate-resilient crops, promotion of micro-irrigation, rainwater harvesting, groundwater regulation, and improved flood-control infrastructure. In conclusion, rainfall variability across North India poses challenges that extend beyond climatology, directly shaping

food security and water resource planning. Addressing these disparities through integrated and adaptive management is essential for sustainable development.

Key words: Rainfall variability, North India, IMD data, agriculture, water resources.

INTRODUCTION

Rainfall is one of the most important factors that affect farming, water supply, and the balance of nature in India. The amount and timing of rain, and how it changes from place to place, strongly shape local economies, food security, and how water is managed. North India is a good example of this diversity—it includes the fertile Indo-Gangetic Plains, the hilly Himalayan foothills, and the dry regions of Rajasthan. Because of this mix, rainfall patterns in the region vary a lot and are influenced by the southwest monsoon, western disturbances, and local weather systems. Looking at states like Uttar Pradesh, Punjab, Haryana, Rajasthan, Uttarakhand, Himachal Pradesh, and Delhi help us understand how different the rainfall situation can be. Farmers in North India rely heavily on rainfall for their crops, even though many areas have well-developed irrigation systems. Changes in when the rains start, how long they last, how heavy they are, and where they fall all effect sowing, crop growth, and harvests. Too much rainfall can cause floods and waterlogging, while too little can bring droughts—both of which hurt farming communities. Rainfall also plays a big role in the availability of water. It decides how much water goes into rivers, how much groundwater is refilled, and how well reservoirs can store water. When rainfall is uneven, it creates imbalances in these systems, making it harder to manage water resources in a sustainable way. Here are discussed some literature reviews on the topic.

Anand, S. and others (2025), examined precipitation trends in North Bihar's Bagmati-Kosi Doab region from 2002-2023, employing Modified Mann-Kendall trend tests and Sen's slope estimators. The research revealed a significant declining rainfall trend of -8.86 mm/year, with potential evapotranspiration consistently high at 2,300-2,700 mm annually while actual evapotranspiration fluctuated between 400-700 mm. Agricultural productivity analysis showed differential crop responses: maize demonstrated steady improvement despite declining rainfall, wheat showed moderate growth, and rice remained stagnant due to its water-intensive nature. The study emphasized urgent needs for efficient irrigation methods, rainwater harvesting, balanced groundwater usage, and integrated watershed management to address increasing agricultural water stress and declining precipitation patterns in the region.

Sharma, G. K. and others (2024), advanced climate modelling research analyzed extreme rainfall events across India using downscaled CMIP6 models under anthropogenic warming scenarios. The study employed 17 General Circulation Models with 0.25° resolution, revealing that extreme rainfall thresholds averaged 48.6 mm/day in observations, improving by 66% after bias correction. Future projections under SSP5-8.5 scenarios indicated 21% increases in extreme rainfall thresholds by 2071-2100, with affected areas expanding 18%. Long-duration extreme events showed two-

fold increases compared to short-duration events, associated with 2.4°C sea surface temperature warming. These findings highlight significant flood risks during monsoon periods, requiring enhanced water management infrastructure and climate adaptation policies for agriculture and water resource management in monsoon-dependent regions.

Sheik, T. (2025) did a 68-year analysis (1950-2018) of rainfall patterns across four Upper Kumaon Himalayan districts revealed continuous decreases in annual precipitation, with Bageshwari experiencing the most severe decline at -3.88 mm/year. Seasonal analysis showed particularly concerning monsoon rainfall decreases, with Almora experiencing -3.28 mm/year reductions. Spatial variability analysis demonstrated that lower-altitude districts like Champawat exhibited higher rainfall variability compared to high-altitude districts such as Pithoragarh. Given that over 75% of the population depends on agriculture and forestry, these declining and increasingly variable rainfall patterns pose significant threats to livelihoods and food security. The study emphasized urgent needs for district-specific adaptation strategies, climate-resilient crops, improved water management, and enhanced disaster preparedness in fragile mountain ecosystems.

Yadav, V. S. and others (2025), analysed rainfall variability and drought patterns across 14 Bundelkhand districts from 1984-2023 employed Pettitt's test, Durbin-Watson test, and rainfall departure methods. The study revealed significant spatial variations, with southern districts (Sagar, Tikamgarh, Panna) receiving higher rainfall than northern districts (Jalaun, Hamirpur, Banda). Drought assessment showed northern Bundelkhand experiences frequent droughts every 4-5 years, with Jalaun exhibiting the highest rainfall variability and Chhatarpur showing more stability. Coefficient of variation analysis and homogeneity testing confirmed irregular rainfall patterns across most districts. These findings provide crucial insights for developing region-specific drought mitigation measures, improved water storage infrastructure, and enhanced agricultural adaptation strategies for this semi-arid, drought-prone region.

In recent decades, climate change has further intensified rainfall variability in North India, with an increase in the frequency of extreme rainfall events, erratic monsoon behavior, and prolonged dry spells. Such changes not only threaten food security but also exacerbate water scarcity, inter-state water conflicts, and environmental degradation. Consequently, understanding spatial rainfall variability is not merely an academic exercise but a pressing requirement for policy formulation, agricultural planning, and water resource management.

This study focuses on analyzing the spatial patterns of rainfall across different states of North India and examining their implications for agriculture and water resources. By identifying variability trends, highlighting vulnerable regions, and linking rainfall

distribution to agricultural outcomes, the research seeks to provide insights for sustainable development and climate resilience in the region.

Objectives

1. To identify spatial variability of rainfall across different states of North India.
2. To discuss the implications of rainfall variability on agriculture.

Methodology

Rainfall variability plays a crucial role in shaping the agricultural economy and water resource management strategies of North India. The region extends from the arid zones of northwestern Rajasthan to the Himalayan ranges of Himachal Pradesh, Uttarakhand, and Jammu & Kashmir, and the fertile alluvial plains of Uttar Pradesh, Punjab, and Haryana. This geographical diversity creates distinct rainfall patterns, with strong dependence on the southwest monsoon and winter western disturbances. The analysis presented here is based on secondary data from the India Meteorological Department (IMD), covering long-term averages (1901–2020) and highlighting the spatial variability of rainfall across major states. Special attention is given to the implications of this variability for agriculture, given that these sectors are the most vulnerable to rainfall fluctuations. In this study, rainfall data from different states of North India was carefully processed and analyzed to understand patterns and variability. First, the Mean Annual Rainfall was calculated for each state to get a general idea of how much rain they usually receive. Then, the Standard Deviation (SD) and Coefficient of Variation (CV) were worked out to measure how much the rainfall changes from year to year. It is a statistical measure used to show how much variability (fluctuation) there is in rainfall relative to its average. Below is given its formula coefficient of variation.

$$CV = \frac{\text{Standard Deviation of Rainfall}}{\text{Mean Rainfall}} \times 100$$

Meaning in rainfall studies:

Low CV (10–20%) → Rainfall is relatively stable and reliable (less fluctuation year to year).

Moderate CV (20–30%) → Rainfall shows moderate variability, some years may be much wetter/drier.

High CV (>30%) → Rainfall is highly erratic and uncertain, making agriculture and water planning risky.

A higher CV value meant that the rainfall was more uncertain and irregular. To make the findings clearer, graphs and line plots were prepared separately for each state, showing

the ups and downs of rainfall over time. A comparative analysis was then done to bring out the differences between regions – such as dry areas like Rajasthan and Haryana, semi-arid zones like Punjab and Uttar Pradesh, humid areas like Bihar, and mountainous regions like Jammu & Kashmir, Himachal Pradesh, and Uttarakhand. Secondary data has been used to analyse the impacts of rainfall variability on major crops of their high production states. Graphs have been used to present the trend of rainfall variability and major crops decline.

Results and Discussions

Spatial Variability of Rainfall across North Indian States

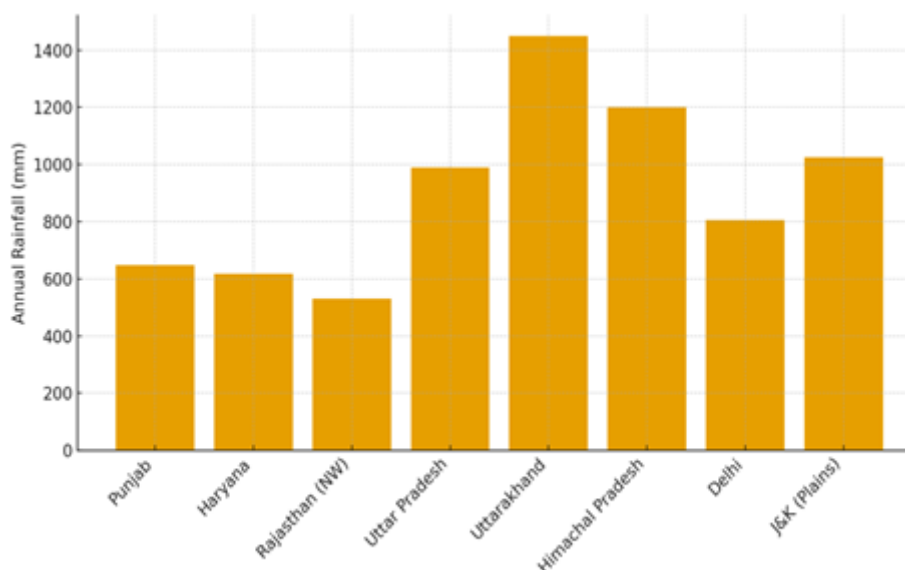
North India experiences an average annual rainfall ranging from 531 mm in northwestern Rajasthan to 1450 mm in Uttarakhand. The sharp differences are linked to topography, geographical position, and monsoon intensity.

Table 1: Rainfall and Variability across North Indian States

State	Annual Rainfall (mm)	Coefficient of Variation (%)
Punjab	649	25
Haryana	617	23
Rajasthan (NW)	531	30
Uttar Pradesh	990	18
Uttarakhand	1450	20
Himachal Pradesh	1200	21
Delhi	805	22
J&K (Plains)	1025	19

(Source: IMD, 2021)

State Wise Rainfall Variability



Source: Indian Meteorology Department

State-wise Rainfall Variability

Punjab

As the table 1 and graph 1 shows Punjab receives around 649 mm of rainfall annually, mainly during July–September. With a CV of 25%, it shows high variability. Central and western districts like Bathinda and Mansa often face drought-like conditions, forcing farmers to rely on groundwater irrigation, further depleting the aquifers.

Haryana

Haryana records about 617 mm of annual rainfall with a CV of 23%. (table 1 and graph 1) Its semi-arid climate makes rainfall irregular, increasing dependence on groundwater for agriculture. Overextraction of aquifers has become a major concern, as limited rainfall fails to meet irrigation demands, threatening long-term water and agricultural sustainability.

Rajasthan

Northwest Rajasthan receives roughly 531 mm of annual rainfall, with the highest CV (30%) in North India. (table 1 and graph 1) Extreme aridity and frequent droughts dominate the region. Agriculture heavily depends on canal irrigation, especially from the Indira Gandhi Canal, but water scarcity continues to hinder sustainable farming practices.

Uttar Pradesh

Uttar Pradesh receives about 990 mm of annual rainfall, showing relatively stable variability (CV 18%). (table 1 and graph 1) However, rainfall distribution is uneven: eastern UP faces recurrent floods due to rivers like the Ganga and Ghaghara, while Bundelkhand in southern UP frequently suffers droughts, posing contrasting agricultural and water challenges.

Uttarakhand

Uttarakhand records nearly 1450 mm of annual rainfall, marked by intense monsoon events. (table 1 and graph 1) With a CV of 20%, variability is moderate but hazardous. Heavy rainfall often triggers flash floods and landslides, as witnessed in the 2013 Kedarnath disaster, endangering lives and property while also replenishing natural water sources.

Himachal Pradesh

Himachal Pradesh receives around 1200 mm of annual rainfall with a CV of 21%. (table 1 and graph 1) The hilly terrain amplifies risks of floods and landslides during monsoon. While hazards disrupt infrastructure and settlements, the rainfall supports horticulture, particularly apple cultivation, making it a vital resource for the state's economy.

Delhi

Delhi experiences about 805 mm of rainfall annually, with a CV of 22%. The city witnesses short, intense monsoon showers leading to waterlogging and urban flooding.

Extended dry spells cause water scarcity, highlighting challenges in balancing rainfall variability with the increasing demands of a rapidly growing urban population.

Jammu & Kashmir (Plains)

The plains of Jammu & Kashmir receive approximately 1025 mm of rainfall annually, with a CV of 19%. Rainfall is generally adequate for agriculture but fluctuates enough to cause periodic floods. Variability in monsoon intensity poses risks for farming communities, affecting crop yields and water management strategies.

Long-term Rainfall Trends

Table 2: Temporal rainfall trends

State	Annual Normal Rainfall (mm)	Trend (1950-2020)	Variability
Punjab	649	Declining	High (CV 25%)
Haryana	617	Declining	High
Rajasthan (NW)	531	Declining	Very High
Uttar Pradesh	990	Fluctuating	Moderate
Uttarakhand	1450	Fluctuating	Moderate
Himachal Pradesh	1200	Stable	Moderate
Delhi	805	Declining	Moderate
J&K (plains)	1025	Stable	Moderate

(Source: IMD, 2021)

Table 2 present about long term fluctuations of these states. North India receives an average annual rainfall of about 975 mm (1901–2020), with notable regional differences. Punjab, Haryana, and Rajasthan show a declining monsoon trend, reducing water availability for crops. Uttar Pradesh and Uttarakhand experience high rainfall variability, causing droughts and floods in alternate years. These trends highlight the need for better water management and climate adaptation strategies.

Seasonal Variability

The rainfall regime of North India reflects a dual system, where both the Southwest Monsoon and winter precipitation act as significant determinants of agricultural productivity. The monsoon season (June–September) contributes approximately 75–85% of the region’s annual rainfall, forming the primary water source for kharif crops such as paddy, maize, and bajra. Consequently, inter-annual variability in monsoon intensity has a direct bearing on crop yields and overall food security. In contrast, winter rainfall (December–February), associated with western disturbances, although limited in volume, plays a disproportionately critical role in sustaining rabi crops,

particularly wheat, across Punjab, Haryana, and western Uttar Pradesh. Fluctuations in winter rainfall therefore translate into notable variations in wheat output, making it an equally important climatic factor for the agrarian economy of these areas. Taken together, the interplay between monsoon rainfall and winter rains underscores the high climatic sensitivity of North Indian agriculture, where even small deviations in precipitation patterns can significantly affect productivity outcomes.

Frequency of Droughts and Wet Years

Major Drought Years: 1965, 1972, 1979, 1987, 2002, 2009, and 2015 saw below-normal rainfall in North India as per IMD data.

Wet Years: According to IMD years, 1994, 2013, and 2019 witnessed above-normal rainfall leading to floods in Uttarakhand, Himachal Pradesh, and UP. The analysis of IMD data highlights significant differences in the annual rainfall received by different states in North India:

High Rainfall States: Uttarakhand (1450 mm) and Himachal Pradesh (1200 mm) record the highest annual rainfall due to their Himalayan location, orographic rainfall, and influence of monsoon currents.

Moderate Rainfall States: Uttar Pradesh (990 mm) and J&K plains (1025 mm) fall in the medium range, with contributions from both the southwest monsoon and winter western disturbances.

Low Rainfall States: Punjab (649 mm), Haryana (617 mm), Delhi (805 mm), and northwestern Rajasthan (531 mm) receive considerably less rainfall, reflecting semi-arid to sub-humid climatic conditions.

Table 3 Average Annual Rainfall and Variability across North Indian States

States	Rainfall Coefficient of Variation (%)	Category (IMD)
Haryana	23	Semi-arid
Rajasthan (NW)	30	Arid
Uttar Pradesh	18	Sub-humid
Uttarakhand	20	Humid/Himalayan
Himachal Pradesh	21	Humid/Himalayan
Delhi	22	Semi-arid to sub-humid
J&K (Plains)	19	Sub-humid

(Source: IMD, 2021)

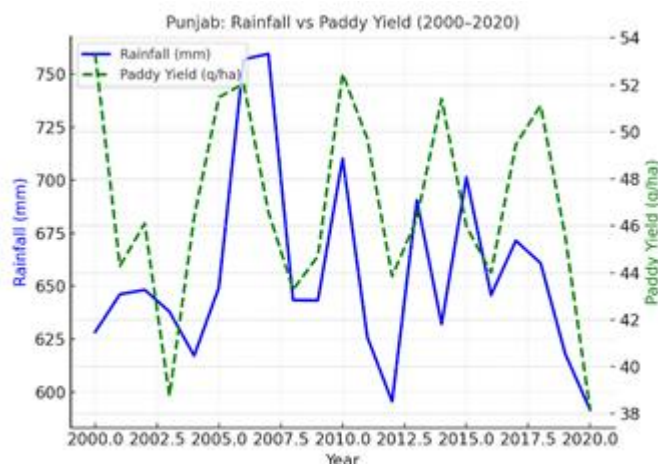


Figure:2

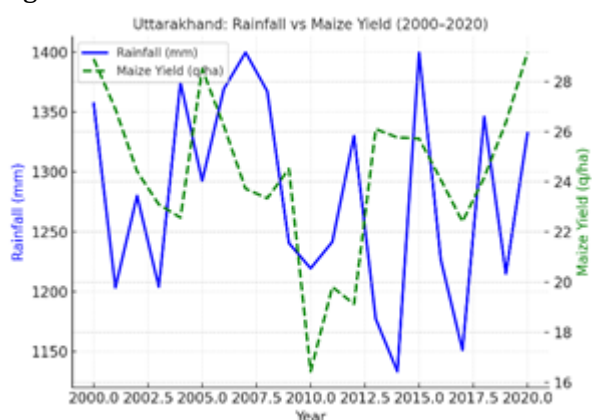


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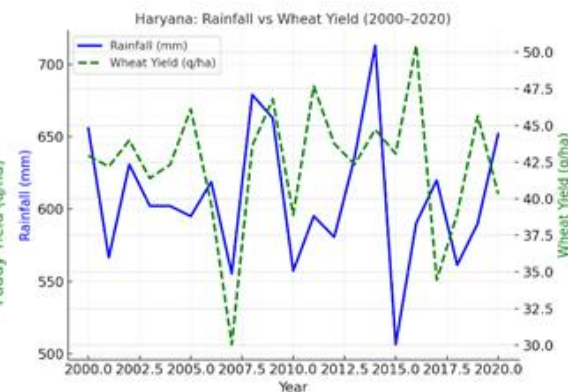


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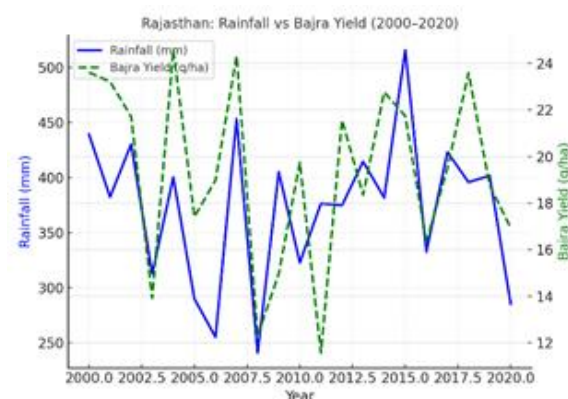


Figure: 5

1. Punjab

The figure 2 shows that rainfall in Punjab fluctuates between 600–750 mm from 2000 to 2020. Paddy yields generally follows the rainfall pattern—higher rainfall years like 2007, 2010, and 2015 see higher paddy production, while low rainfall years such as 2003, 2012, and 2020 show reduced yields. This indicates that paddy crops are highly dependent on monsoon rainfall.

2. Haryana

In figure 3, rainfall in Haryana varies between 500–700 mm. Wheat yield shows some correlation with rainfall but is slightly more stable. Extreme low rainfall years (e.g., 2015) cause a significant drop in wheat yield. This suggests wheat is moderately sensitive to rainfall variability, but irrigation may help reduce yield losses.

3. Uttarakhand

Uttarakhand receives heavy rainfall, 1150–1400 mm. Maize yield shows fluctuations, often increasing after high rainfall years and decreasing in deficit years. (figure 4) This

reflects that maize growth depends on adequate water but may also be affected by other factors like soil and terrain.

4. Rajasthan

Rajasthan has the lowest rainfall (250–500 mm). Bajra yield closely follows rainfall trends—low rainfall years like 2006, 2010, and 2020 result in lower yields. (figure 5) Since Bajra is a drought-resistant crop, yield still varies significantly under extreme dry conditions.

Overall, it is observed that in Punjab, where rainfall ranges between 600–750 mm, paddy production is highly dependent on monsoon rains, showing clear increases in good rainfall years like 2007, 2010, and 2015, while poor rainfall years such as 2003, 2012, and 2020 see sharp declines. In Haryana, rainfall is slightly lower at 500–700 mm, and wheat yields, though somewhat related to rainfall, are more stable, possibly because irrigation reduces the impact of low rainfall; however, extreme deficit years like 2015 still cause noticeable yield drops. Uttarakhand, with its higher rainfall of 1150–1400 mm, shows fluctuations in maize yield, which generally improves in years with abundant rain but sometimes declines despite good rainfall, suggesting that other factors like soil conditions, terrain, and management practices also influence productivity. Rajasthan, the driest among these states with rainfall between 250–500 mm, grows bajra, a drought-resistant crop, yet even it shows strong dependence on rainfall trends, with poor harvests in very dry years like 2006, 2010, and 2020. Overall, while irrigation and crop type influence resilience, rainfall remains the most critical factor shaping agricultural output across these regions.

Conclusion

The analysis of annual rainfall trends across North-West India (1950–2020) highlights significant spatial and temporal variability. Arid regions like Rajasthan and Haryana show persistently low and highly erratic rainfall, posing severe risks to agriculture and water security. Semi-arid states such as Punjab and western Uttar Pradesh demonstrate heavy dependence on irrigation, leading to unsustainable groundwater extraction. Mountainous states like Uttarakhand and Himachal Pradesh reveal a contrasting scenario, with excessive rainfall events triggering flash floods, landslides, and crop damage. Meanwhile, eastern Uttar Pradesh and Bihar display relatively stable rainfall but remain vulnerable to recurrent floods. The dual nature of rainfall extremes—droughts in arid zones and floods in humid/mountainous regions—indicates increasing climatic uncertainty. This has direct consequences for agriculture, groundwater sustainability, river flow variability, and disaster management across the region.

RECOMMENDATIONS

A. Sustainable Agriculture Practices

1. Promote drought-resistant crop varieties (e.g., millet, pulses) in arid/semi-arid states.

2. Encourage crop diversification in Punjab and Haryana to reduce paddy-wheat dependency.
3. Strengthen terrace farming and soil conservation in Himalayan states to minimize erosion.

B. Water Resource Management

- Expand artificial recharge structures (check dams, recharge wells) in groundwater-stressed states.
- Integrate rainwater harvesting into urban and rural planning.
- Develop basin-level strategies for equitable river water allocation.

C. Flood and Drought Preparedness

- Establish early-warning systems using IMD data and satellite monitoring for floods and cloudbursts.
- Improve embankments and drainage systems in flood-prone areas of eastern UP and Bihar.
- Launch contingency crop insurance schemes for drought-hit farmers.

D. Community Awareness and Participation

- Train farmers in climate-resilient practices through Krishi Vigyan Kendras (KVKs).
- Promote village-level water budgeting and participatory watershed management.

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