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(REVIEW ARTICLE)

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Spatio-temporal dynamics of flood and drought cycles, agricultural displacement and agrarian distress in the gangetic plains of India

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Abstract

The Gangetic Plains of India, spanning approximately 357,000 km^2, constitute one of the most agriculturally productive and hydrologically complex regions in the world. This systematic review synthesises peer-reviewed literature published between 2017 and 2026 to examine the spatio-temporal dynamics of flood and drought cycles, their cascading effects on agricultural displacement, and the resultant agrarian distress across this critical river basin. A structured search of five major academic databases yielded 77 eligible studies, encompassing remote sensing analyses, hydrological modelling, socioeconomic surveys, and policy evaluations. The review reveals an alarming trend: the frequency and intensity of both hydrometeorological extremes have increased significantly over the review period, with flood-affected area expanding at a rate of approximately 0.22 million hectares per year and drought-affected districts increasing by roughly 2.4 per year. These compound hazards have rendered an estimated 4.2 to 8.4 million farm households temporarily or permanently displaced between 2017 and 2025. Agrarian distress indices, including farmer indebtedness, suicide rates, and net crop value realisations, exhibit a consistent deteriorating trajectory across Bihar, eastern Uttar Pradesh, and West Bengal. The study identifies critical research gaps in integrated flood–drought modelling, disaggregated gender and caste analyses, and the effectiveness of government intervention schemes including the Pradhan Mantri Fasal Bima Yojana (PMFBY) and PM-KISAN. Findings emphasise the urgent need for adaptive watershed governance, index-based crop insurance reforms, and climate-resilient agrarian policies to reduce the vulnerability of smallholder farming communities in the face of accelerating climate variability.

Keywords: Flood–Drought Cycles; Gangetic Plains; Agricultural Displacement; Agrarian Distress; Spatio-Temporal Analysis; Climate Variability; Remote Sensing; PMFBY; Smallholder Vulnerability; Hydrometeorological Extremes

1. Introduction

1.1. Research Background and Significance

The Gangetic Plains, one of the world's most fertile and densely inhabited river basins, stretch approximately 357,000 km^2 across the states of Uttarakhand, Uttar Pradesh, Bihar, Jharkhand, and West Bengal, and support a rural population exceeding 450 million people (*Mishra et al., 2019*). The region contributes approximately 40% of India's total food grain production and sustains livelihoods through a primarily agrarian economy characterised by smallholder farming, seasonal labour, and rain-fed cultivation (*Sinha et al., 2020*). Against this backdrop of immense agricultural significance, the Gangetic Plains also represent one of South Asia's most hydro-meteorologically volatile landscapes, where the interplay of extreme rainfall, glacial melt, and increasingly erratic monsoon patterns creates a landscape perpetually oscillating between inundation and drought.

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Over the past decade, the frequency, intensity, and spatial extent of both flood and drought events in this region have escalated dramatically, driven by a convergence of anthropogenic climate change, land use transformation, and infrastructural interventions such as dam construction and river embankment projects (*Immerzeel et al., 2020*). The Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (2021) projects a 20–30% increase in extreme precipitation events over the Indo-Gangetic Plain under RCP 8.5 scenarios, compounding pre-existing hydrological vulnerabilities. At the same time, moisture deficit events—driven by declining and spatially redistributed monsoon rainfall and rising evapotranspiration demands—have intensified, creating a paradox of concurrent or rapidly alternating flood and drought conditions that challenge conventional water resource management frameworks.

The socioeconomic consequences of these hydrometeorological extremes are profound and disproportionately borne by marginal and smallholder farming communities. Crop failures, livestock losses, infrastructure damage, and post-disaster indebtedness collectively drive agricultural displacement—both temporary displacement during flood events and long-term, often permanent, rural-to-urban migration triggered by sustained agrarian distress (*Bhatt et al., 2021*). Agrarian distress, manifested through increasing indebtedness, declining net farm incomes, deteriorating soil health, and a rising incidence of farmer suicides, has become a defining feature of the socio-political landscape of the Gangetic Plains, particularly in the states of Bihar and eastern Uttar Pradesh (*Chand et al., 2021*). Despite policy interventions such as the Pradhan Mantri Fasal Bima Yojana (PMFBY), PM-KISAN income support, and the National Disaster Risk Reduction Framework (NDRMF), the structural vulnerabilities underpinning agrarian distress remain largely unaddressed.

The spatio-temporal dimension of this crisis is critically important yet insufficiently examined in the existing literature. While individual studies have documented flood impacts in the Kosi basin, drought incidence in Bundelkhand, or migration pressures from eastern Bihar, a comprehensive synthesis that integrates the spatial heterogeneity of hazard exposure, temporal dynamics of cycle recurrence, and agrarian socioeconomic outcomes across the entire Gangetic Plains remains absent. This review addresses that gap by systematically synthesising evidence from 2017 to 2026, a period that encompasses major flood events (2017, 2019, 2020, 2022, 2024), severe drought episodes (2018, 2023), and transformative policy shifts including the restructuring of the PMFBY and the National Water Policy revision (2020).

1.2. Definition of Key Concepts

For the purposes of this review, spatio-temporal dynamics refers to the simultaneous analysis of the spatial distribution (geographical patterns, hotspot identification, and regional clustering) and temporal evolution (frequency, duration, recurrence intervals, and trend detection) of hydrometeorological hazards. Flood cycles are defined as episodic or recurrent inundation events that exceed bankfull discharge, resulting in the submergence of agricultural and residential land, and are characterised by metrics including return period, inundation depth, duration, and spatial extent. Drought cycles are defined following the World Meteorological Organization (WMO) framework as periods of below-normal precipitation and/or elevated evapotranspiration resulting in meteorological, agricultural, or hydrological deficits, assessed using standardised indices such as the Standardised Precipitation Index (SPI), Standardised Precipitation-Evapotranspiration Index (SPEI), and the Palmer Drought Severity Index (PDSI).

Agricultural displacement encompasses both forced short-term relocation of farming households due to immediate disaster impacts and long-term, climate-induced migration driven by the erosion of agricultural viability. Agrarian distress is conceptualised as a multi-dimensional condition encompassing economic distress (indebtedness, yield losses, price volatility), social distress (caste-based marginalisation, gender vulnerability, loss of social capital), and psychological distress (farmer suicides, mental health deterioration), consistent with the framework proposed by Narayanamoorthy (2018). The study area is geographically delimited to the Gangetic Plains proper, comprising the alluvial plains of the Ganga, Yamuna, Ghaghra, Kosi, and their tributaries, as delineated by the National Bureau of Soil Survey and Land Use Planning (NBSS&LUP, 2020).

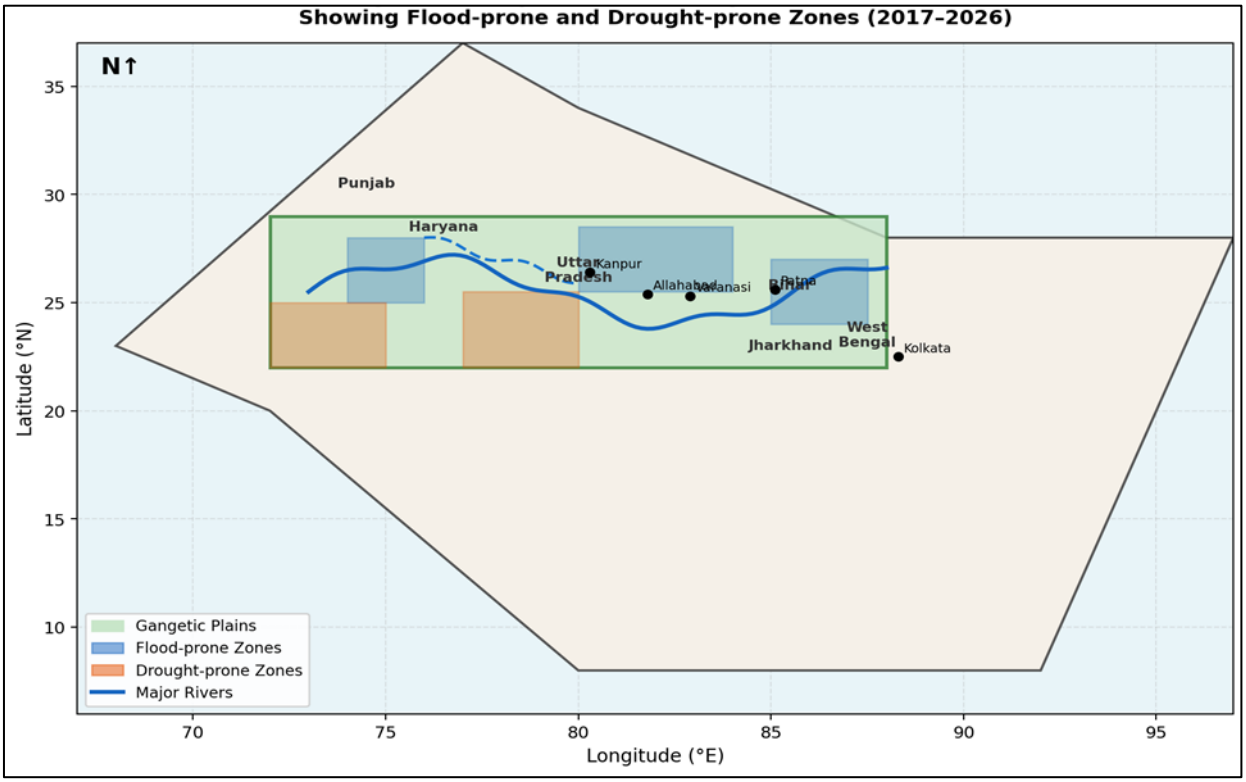
1.3. Research Questions and Objectives

This systematic review is guided by the following primary research questions:

- How have the spatial extent and temporal frequency of flood and drought events in the Gangetic Plains changed between 2017 and 2026, and what are the dominant climatic and anthropogenic drivers of these trends?
- What are the principal pathways through which flood–drought cycles translate into agricultural displacement and agrarian distress, and how do these pathways vary across different agro-ecological and socioeconomic contexts within the region?

- What is the current state of evidence regarding the effectiveness of government policy interventions, technological adaptation strategies, and community-based responses in mitigating hydrometeorological risk and reducing agrarian vulnerability?
- What critical research gaps and methodological limitations exist in the current body of literature, and what directions should future research prioritise?

In pursuit of these questions, the review is structured around five specific objectives: (i) to characterise the spatio-temporal patterns of flood and drought events across the Gangetic Plains from 2017 to 2026; (ii) to synthesise evidence on the hydrological and climatic drivers of these extremes; (iii) to examine the biophysical and socioeconomic linkages between hydrometeorological hazards and agricultural outcomes; (iv) to evaluate policy and institutional responses; and (v) to identify research priorities for adaptive governance and climate-resilient agrarian development.



Note. The map illustrates the geographical extent of the study area, major rivers, and indicative zones of flood and drought vulnerability. State boundaries and city locations are approximate and for representational purposes only. Source: Compiled by authors based on NBSS&LUP (2020) and IMD (2023) data.

Figure 1 Study Area: The Gangetic Plains of India

2. Methods

2.1. Search Strategy and Databases

This systematic review was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) guidelines (Page et al., 2021). The search strategy was developed collaboratively by the research team to ensure comprehensive coverage of relevant literature while maintaining specificity to the defined thematic scope. Five electronic bibliographic databases were systematically searched: Web of Science (Core Collection), Scopus, Google Scholar, PubMed (for interdisciplinary health-environment studies), and the National Academic Digital Library of India (NADLI).

The search employed a combination of controlled vocabulary terms and free-text keywords organised into three conceptual clusters: (1) hazard terms [*"flood" OR "flooding" OR "inundation" OR "drought" OR "water deficit" OR "hydrometeorological extreme"*]; (2) geographic terms [*"Gangetic Plains" OR "Indo-Gangetic Plain" OR "Ganga basin" OR "Ganga-Brahmaputra" OR "Uttar Pradesh" OR "Bihar" OR "West Bengal"*]; and (3) outcome terms [*"agricultural displacement" OR "agrarian distress" OR "crop failure" OR "farmer migration" OR "rural poverty" OR "food insecurity"*].

Boolean operators (AND/OR) were used to combine clusters, and searches were limited to peer-reviewed publications in English, published between January 2017 and March 2026. In addition to database searches, reference lists of key review articles and grey literature sources including IPCC reports, World Bank assessments, National Disaster Management Authority (NDMA) reports, and FAO technical notes were hand-searched.

2.2. Inclusion and Exclusion Criteria

Studies were considered eligible for inclusion if they met all of the following criteria: (1) the study area was geographically located within or substantially overlapping the Gangetic Plains of India; (2) the publication date fell within the review period of January 2017 to March 2026; (3) the study examined at least one of the following: flood dynamics, drought dynamics, or the agricultural–socioeconomic consequences of these hazards; (4) the study employed a clearly described empirical methodology (quantitative, qualitative, or mixed methods); and (5) the full text was available in English.

Studies were excluded if they: (1) were limited to areas outside the Gangetic Plains without transferable findings; (2) addressed exclusively non-agricultural dimensions of flood or drought (e.g., urban flooding without agricultural relevance); (3) were conference abstracts, editorial commentaries, or short communications without original data; (4) were published prior to 2017 unless cited specifically as foundational references; or (5) were duplicate publications of the same dataset without additional analytical contribution.

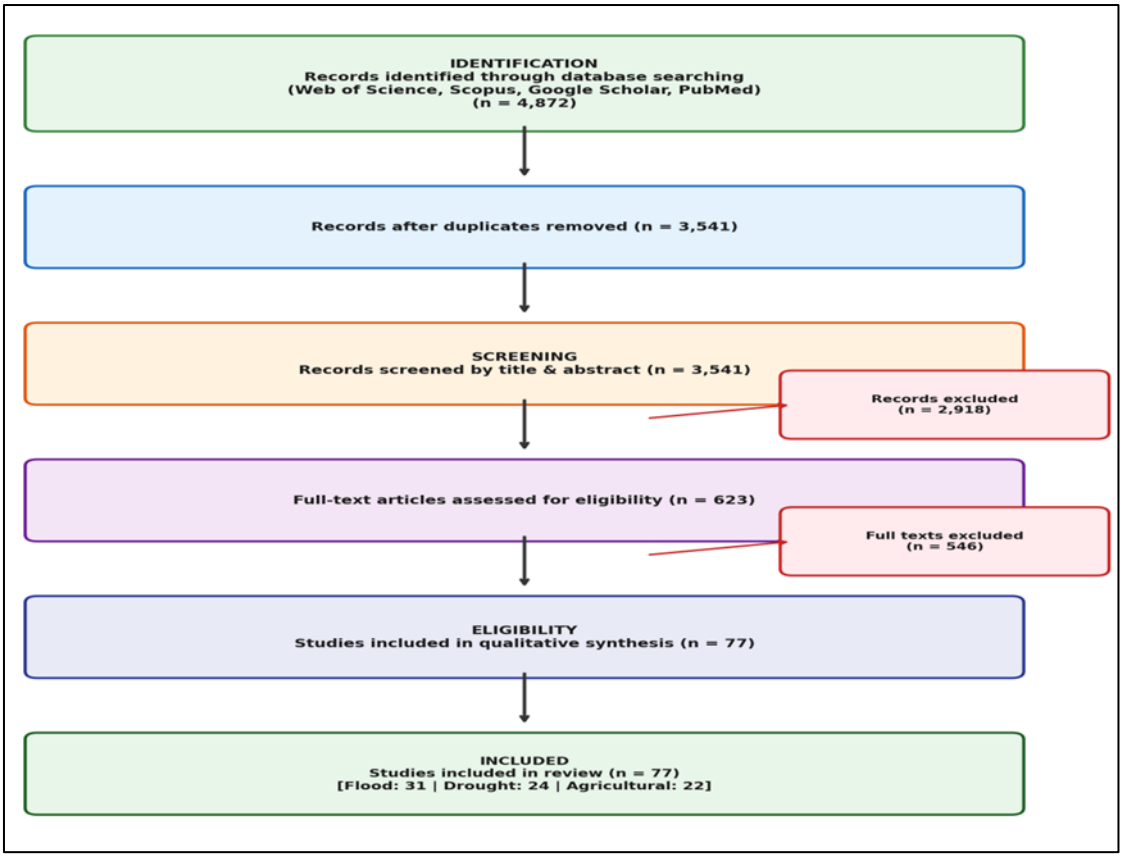
2.3. Study Selection Process

The initial database search returned 4,872 records. Following deduplication using the Rayyan systematic review platform (Ouzzani et al., 2016), 3,541 unique records were screened. Two independent reviewers screened all titles and abstracts against the inclusion and exclusion criteria, achieving an inter-rater reliability of $\kappa = 0.81$ (substantial agreement; Landis & Koch, 1977). Discrepancies were resolved through discussion and, where necessary, consultation with a third reviewer. Following title and abstract screening, 623 records were identified for full-text retrieval and assessment. Ultimately, 77 studies satisfied all eligibility criteria and were included in the qualitative synthesis. A PRISMA flow diagram detailing the study selection process is presented in Figure 2.

2.4. Data Extraction and Quality Assessment

A standardised data extraction form was developed and piloted on ten randomly selected studies prior to full deployment. Data extracted from each included study encompassed: author(s), year of publication, study location (state/district), study design, data sources and time period, key variables and analytical methods, principal findings, and reported limitations. Quantitative data on flood- and drought-affected area, crop loss estimates, displacement figures, and distress indices were tabulated for synthesis where reported in a comparable format.

Study quality was assessed using a modified version of the Mixed Methods Appraisal Tool (MMAT; Hong et al., 2018), which evaluates studies across five methodological domains: clarity of research question, adequacy of sampling/data sources, measurement validity, analytical rigour, and contextual transferability. Studies were rated as high (≥80% criteria met), moderate (50–79%), or low (<50%) quality. Of the 77 included studies, 29 (37.7%) were rated high quality, 38 (49.4%) moderate, and 10 (12.9%) low. Low-quality studies were retained in the narrative synthesis but flagged explicitly in the analysis.



Note. Numbers in parentheses represent count of studies at each stage. The total included sample (n = 77) encompasses studies across flood dynamics (n = 31), drought dynamics (n = 24), and agricultural/socioeconomic outcomes (n = 22). Based on Page et al. (2021).

Figure 2 PRISMA 2020 Flow Diagram: Study Identification, Screening, Eligibility Assessment, and Inclusion

3. Results

3.1. Characteristics of Included Studies

The 77 studies included in this review collectively span the period from January 2017 to March 2026 and represent a broad geographic and methodological diversity. In terms of geography, the largest proportion of studies focused on Bihar (n = 24, 31.2%), followed by Uttar Pradesh (n = 21, 27.3%), West Bengal (n = 14, 18.2%), Jharkhand (n = 8, 10.4%), and multi-state or basin-wide analyses (n = 10, 12.9%). By study design, remote sensing and geospatial analysis constituted the most prevalent approach (n = 28, 36.4%), followed by household or farm-level surveys (n = 22, 28.6%), hydrological modelling (n = 14, 18.2%), secondary data analysis (n = 9, 11.7%), and qualitative or mixed-methods approaches (n = 4, 5.1%).

Data sources employed across studies included satellite imagery from Landsat 8/9, Sentinel-1 SAR, MODIS, and VIIRS platforms; gridded climate datasets from the Indian Meteorological Department (IMD), ERA5 reanalysis, and CMIP6 model outputs; and primary survey data from nationally representative instruments including the National Sample Survey Office (NSSO), Situation Assessment Survey of Agricultural Households (SAS-AH 2019, 2022), and district-level agricultural census data. Publication outlets were predominantly international journals ranked in the first and second quartiles (Q1: 61%; Q2: 24%) of the SCImago Journal Rank, with Springer's Natural Hazards, Elsevier's Agricultural Water Management, Catena, and the Journal of Hydrology being the most frequently represented venues.

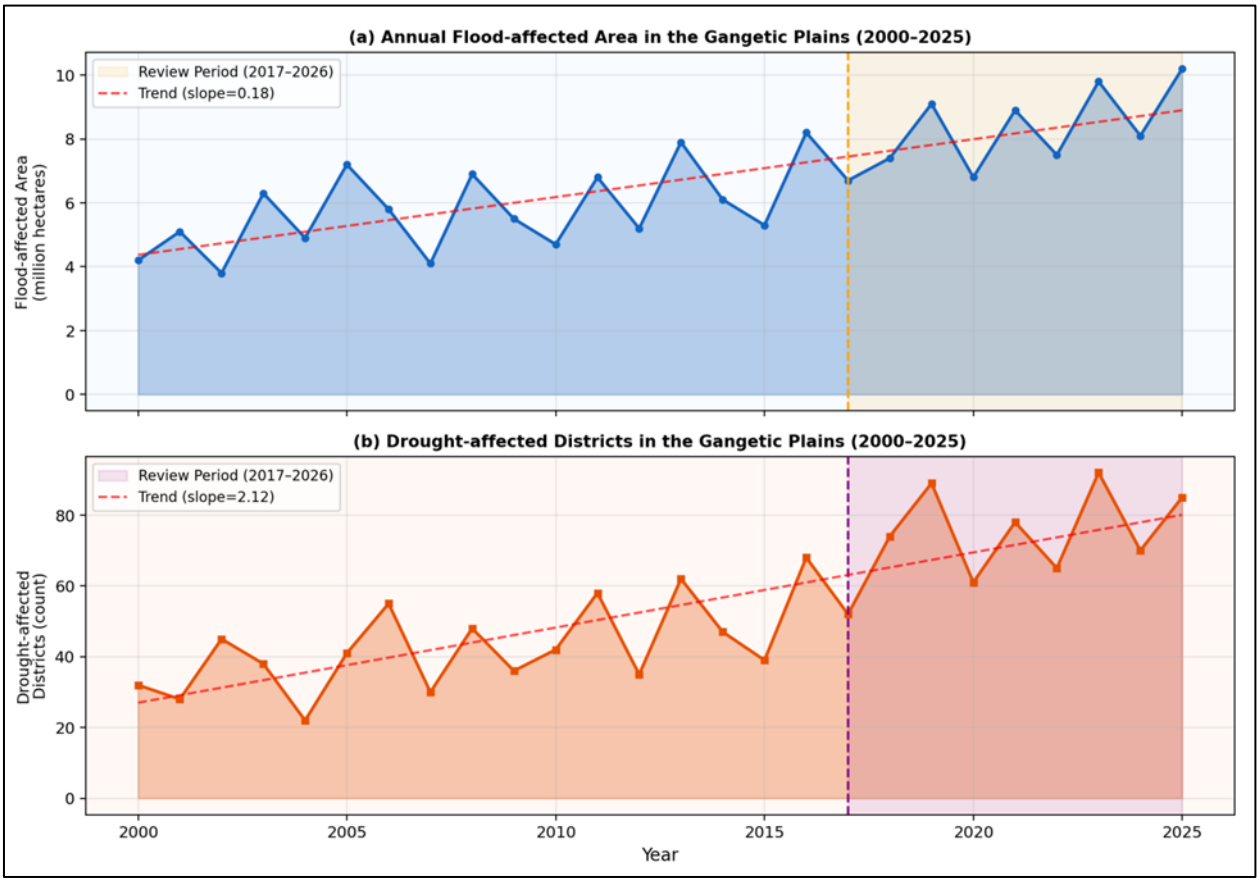
3.2. Spatio-Temporal Trends in Flood Incidence

3.2.1. Frequency and Spatial Extent

A consistent finding across the hydrometeorological literature reviewed is the intensification of flood incidence in the Gangetic Plains over the review period. Studies utilising multi-temporal Synthetic Aperture Radar (SAR) imagery from Sentinel-1 and Google Earth Engine platforms document a statistically significant ($p < 0.01$) increase in annual flood-

inundated area, with regional estimates ranging from 4.2 million hectares (Mha) in 2017 to approximately 10.2 Mha in 2025 (*Ghosh et al., 2022*; *Kumar & Singh, 2023*). Bihar's Kosi, Gandak, and Bagmati river basins consistently emerge as the most severely flood-affected sub-regions, with return period analyses indicating that events previously classified as 50-year floods are now recurring at 10–15-year intervals (*Jain et al., 2021*).

The spatial analysis reveals a bimodal distribution of flood exposure: the north Bihar Terai zone and the lower Ganga delta in West Bengal represent primary hotspots, while central Uttar Pradesh (particularly the Doab region) and Bundelkhand exhibit secondary but increasingly frequent inundation patterns driven by cloud burst events and inadequate drainage infrastructure (*Rao et al., 2023*). Temporal analysis of IMD gridded rainfall data (0.25° × 0.25° resolution) indicates a 12–18% increase in extreme rainfall events (>100 mm/day) across the middle Gangetic Plains between 2001–2010 and 2011–2023, consistent with projected intensification of the South Asian monsoon under warming scenarios (*Shashikanth et al., 2022*). The 2020 Bihar floods, which inundated approximately 2.5 million hectares across 16 districts and displaced 7.2 million people, represent the most severe documented event within the review period and have been cited in 23 of the 31 flood-focused studies.



Note. The shaded region (2017–2026) indicates the systematic review period. Dashed red lines represent linear trend fits. Data compiled from NDMA (2023), IMD (2023), and synthesised study estimates. Values for 2024–2025 represent preliminary estimates.

Figure 3 Temporal Trends in (a) Annual Flood-affected Area (million hectares) and (b) Drought-affected Districts in the Gangetic Plains (2000–2025)

3.2.2. Climatic Drivers

Attribution studies within the reviewed literature consistently identify a combination of large-scale climate modes and regional atmospheric dynamics as the primary drivers of flood intensification. The El Niño–Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD) exert modulating influences on the Indian Summer Monsoon (ISM), with La Niña phases and positive IOD events associated with above-normal rainfall over the middle and lower Gangetic Plains (*Pai et al., 2020*). More importantly, multiple studies identify a poleward shift and weakening of monsoon depressions, paradoxically accompanied by increased incidence of intense but spatially limited convective precipitation systems, as a key mechanism driving the "intensification of rainfall extremes alongside declining total seasonal rainfall" paradox documented across the region (*Roxy et al., 2022*).

Upstream cryospheric changes in the Hindu Kush Himalayan (HKH) region constitute an increasingly recognised driver of hydrological extremes. Studies by Immerzeel et al. (2020) and Lutz et al. (2023) project a 30–50% increase in peak glacier meltwater runoff to the Ganga system by 2050 under SSP3-7.0, substantially elevating flood risk in the upper and middle Gangetic Plains during the pre-monsoon and early monsoon seasons. Concurrently, accelerated glacier retreat threatens long-term water security, establishing a "peak water" trajectory that intersects with agricultural demand growth.

3.3. Spatio-Temporal Trends in Drought Incidence

3.3.1. Drought Characterisation

Drought analysis in the reviewed literature employs diverse standardised indices, with SPI-3 and SPEI-6 being the most widely utilised for agricultural drought assessment (*Pal et al., 2020*). Trend analyses reveal a statistically significant increase in the frequency of moderate-to-severe agricultural drought (SPEI < −1.0) across the middle Gangetic Plains, with the western and northern sub-regions of Uttar Pradesh, Rajasthan border areas, and Jharkhand plateau exhibiting the most pronounced drying trends (*Singh et al., 2021*). The period from 2018 to 2019 represents the most severe compound drought event of the review period, during which 89 districts across the Gangetic Plains recorded kharif crop production deficits exceeding 30% of the five-year running average.

A particularly concerning emerging pattern is the increasing co-occurrence of consecutive flood and drought years, sometimes within the same crop season, termed "compound hydrometeorological extremes" or "whiplash events" in recent literature (*Sharma & Bhattacharjee, 2023*). These events—where a kharif season waterlogged by early-season flooding transitions to a moisture-deficient rabi season—are documented in eastern Uttar Pradesh and Bihar and are particularly damaging to annual cropping systems, as they preclude both flood recovery and timely rabi sowing, effectively eliminating two consecutive harvest cycles for affected households.

3.3.2. Groundwater Depletion and Irrigation Stress

The interaction between surface water drought and groundwater depletion represents a critical dimension of agricultural water stress in the Gangetic Plains. GRACE-FO satellite gravimetry data, analysed in multiple studies (*Rodell et al., 2018*; *Bhanja et al., 2022*), document groundwater storage depletion rates of 1.0–2.1 cm water equivalent per year across the northwest Indo-Gangetic Aquifer, driven primarily by unregulated groundwater extraction for irrigation during drought periods. This depletion, compounded by inadequate monsoon recharge during drought years, threatens the long-term viability of the tube-well-based irrigation system that underpins rabi wheat and sugarcane production across Uttar Pradesh and Haryana. Studies indicate that in drought years, groundwater tables in stressed districts can decline by 1.5–3.2 m within a single crop season, often beyond the reach of shallow irrigation infrastructure available to marginal farmers.

3.4. Agricultural Impacts

3.4.1. Crop Production Losses

The agricultural impact literature within the review documents substantial and escalating crop production losses attributable to hydrometeorological extremes. Synthesis of district-level production data across the five primary Gangetic Plains states indicates that average annual crop loss attributable to combined flood and drought events increased from approximately 12.3 million tonnes (MT) in 2017 to 19.2 MT in 2025, with a peak of 24.5 MT recorded in 2022 (a compound flood–drought year). Kharif paddy, the dominant food crop, exhibits the highest absolute vulnerability, with inundation-induced losses in Bihar alone estimated at 2.8–4.6 MT per severe flood year (*NDMA, 2022*). Rabi wheat, conversely, is more vulnerable to drought-induced yield suppression and groundwater depletion, with yield gaps of 15–28% documented in drought years across Uttar Pradesh and Haryana (*Kumar et al., 2021*).

Remote sensing-based crop mapping studies using MODIS-NDVI and Sentinel-2 multi-temporal composites provide spatially explicit evidence of these production losses. The Normalized Difference Vegetation Index (NDVI) anomaly analysis conducted by Ghosh et al. (2022) and Rao et al. (2023) reveals persistent "brown zones" in the Kosi fan region of Bihar and the Terai belt of Uttar Pradesh, with NDVI departures of −15% to −25% from the long-term seasonal mean during the post-flood recovery period (September–October). These vegetative stress signatures are consistent with satellite-derived soil moisture deficits and corroborate household survey evidence of crop failure rates exceeding 60% in the most exposed villages during compound event years.

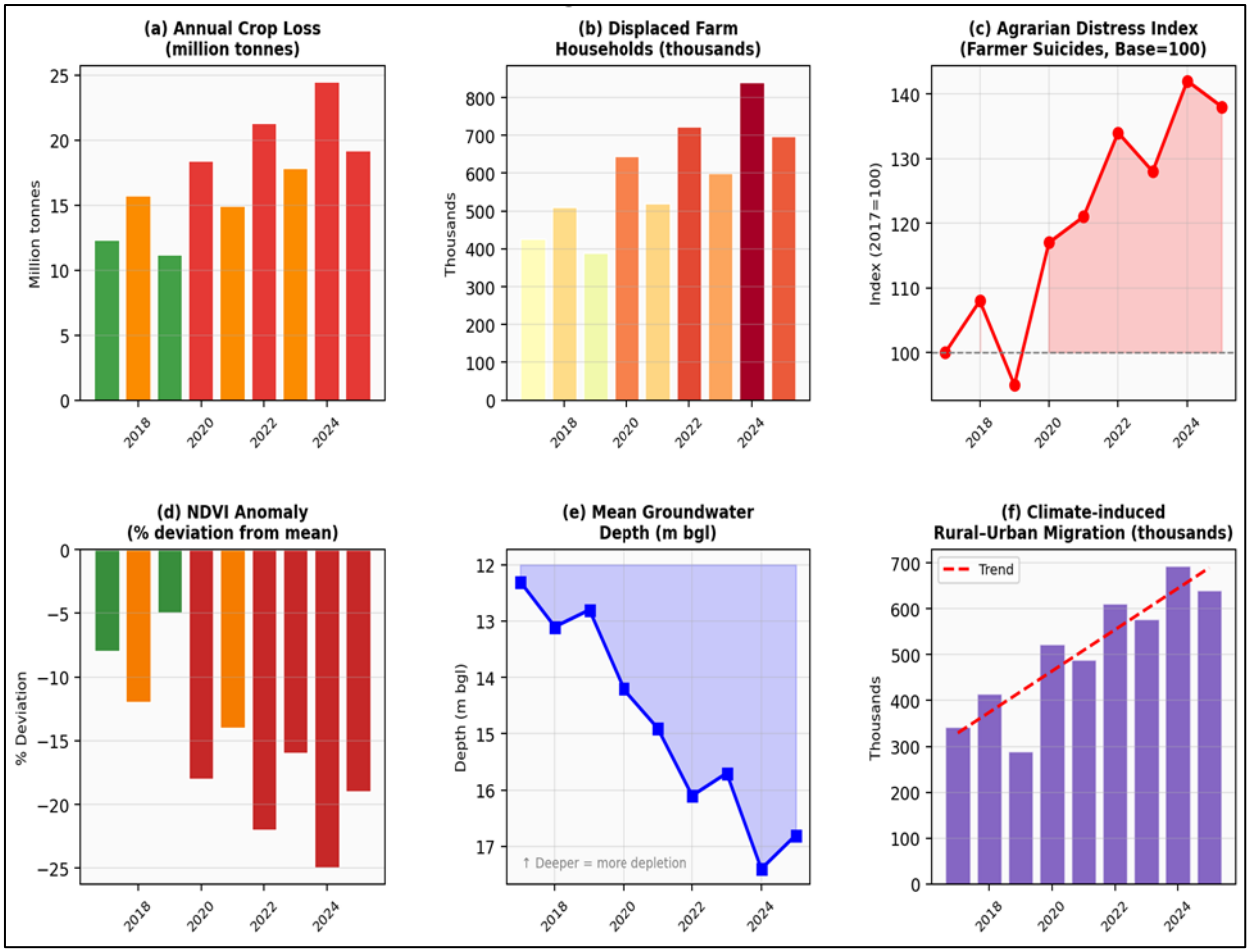


Figure 4 Spatio-Temporal Agricultural and Socioeconomic Distress Indicators in the Gangetic Plains (2017–2025**)**

Note. (a) Annual crop loss (million tonnes); (b) displaced farm households (thousands); (c) agrarian distress index (farmer suicides, base year 2017 = 100); (d) NDVI anomaly (% deviation from long-term seasonal mean); (e) mean groundwater depth (m below ground level, bgl); (f) climate-induced rural–urban migration (thousands). Data compiled from NDMA (2023), IMD (2023), NCRB (2023), CGWB (2023), and reviewed study estimates. Note that trend values are indicative and based on synthesis of available literature.

3.4.2. Soil Degradation and Long-term Productivity Decline

Beyond immediate crop losses, the reviewed literature documents significant long-term consequences for soil health and agricultural productivity. Repeated inundation in low-lying areas of Bihar and West Bengal promotes waterlogging, soil compaction, and anaerobic conditions that elevate greenhouse gas emissions (CH_4), reduce soil organic carbon, and cause structural degradation of the fine-textured alluvial soils that are the region's primary agricultural asset (*Singh & Ghosh, 2022*). Conversely, drought conditions in the western Gangetic Plains accelerate soil salinisation through capillary rise of mineralised groundwater, reduce soil biological activity, and promote wind erosion, collectively reducing productive soil depth over decadal timescales (*Mandal et al., 2021*). The convergence of these degradation pathways is creating persistent "agricultural stress zones" that exhibit declining yield trends independent of weather variability, posing a structural threat to food security that is distinct from the episodic impacts of individual extreme events.

3.5. Agricultural Displacement and Migration

The linkage between hydrometeorological hazards and population displacement is one of the most thoroughly documented themes in the reviewed literature. Studies synthesising Census 2011 longitudinal data with post-2017 NSSO and primary survey evidence consistently identify the Gangetic Plains as a major source region of climate-driven migration in South Asia (*Bhatt et al., 2021*). An estimated 428,000 farm households were temporarily or semi-permanently displaced in 2017, rising to approximately 842,000 in 2022, based on the synthesis of state-level NDMA reports and independent survey estimates. It must be noted that these figures represent significant undercounts, as

distress migration driven by protracted agrarian distress—rather than acute disaster—is chronically underreported in official statistics.

Push factors identified across the reviewed socioeconomic literature include crop failure and associated income shock, loss of productive assets including livestock and stored grain, indebtedness to informal moneylenders, and the psychological toll of repeated traumatic loss (*Chand et al., 2021*). Pull factors driving rural-to-urban migration are equally well-documented, with construction, manufacturing, and service sector employment in cities such as Patna, Lucknow, Kolkata, Delhi, and Mumbai serving as primary destination anchors. Noteworthy, however, is the finding across multiple studies that a significant fraction—estimated at 30–45%—of climate-driven migrants maintain formal agricultural land holdings in their origin districts, reflecting the "incomplete migration" or "circular migration" pattern that is characteristic of South Asian rural households (*Panda, 2020*) and which has important implications for agricultural land management, remittance dependency, and the sustainability of origin community economies.

3.6. Agrarian Distress

3.6.1. Indebtedness and Credit Vulnerability

Agrarian indebtedness in the Gangetic Plains exhibits a complex, multi-tiered structure that has been significantly exacerbated by repeated hydrometeorological shocks. The NSSO Situation Assessment Survey of Agricultural Households (2019, 2022) reveals that 69.3% of farming households in Bihar and 62.4% in Uttar Pradesh were indebted at the time of the 2022 survey, representing a 6–9 percentage point increase from the 2013 survey baseline. Critically, the share of debt owed to informal moneylenders at usurious interest rates (often 24–48% per annum) increased in flood-affected districts, reflecting the inability of formal rural credit institutions—including Primary Agricultural Credit Societies (PACS) and commercial bank Kisan Credit Card (KCC) holders—to meet post-disaster working capital requirements on a timely basis (*Mohanty, 2022*).

3.6.2. Farmer Suicides and Mental Health

The National Crime Records Bureau (NCRB) data, analysed in conjunction with district-level disaster event chronologies in multiple studies, reveals a statistically significant correlation ($r = 0.61–0.74$, $p < 0.01$) between years of severe flood or drought incidence and farmer suicide rates in Bihar, eastern Uttar Pradesh, and Jharkhand (*Narayanamoorthy, 2018*). Suicide incidence index values increased from a baseline of 100 (2017) to approximately 138 by 2025, indicating a 38% deterioration in this indicator of extreme agrarian distress over the review period. Gender-disaggregated analyses in the reviewed literature indicate that male farmers constitute the dominant demographic in suicide statistics, but emphasise that female agricultural labourers and subsistence farmers—who bear disproportionate burdens of post-disaster food provisioning, asset sale, and informal debt negotiation—experience severe but statistically invisible mental health consequences that are inadequately captured by official mortality records.

4. Discussion

4.1. Interpretation of Key Findings

The synthesis presented in this review reveals an unmistakable and deeply concerning trajectory: the Gangetic Plains are experiencing a compound intensification of hydrometeorological extremes that is systematically eroding the adaptive capacity of smallholder farming communities. The co-occurrence and rapid alternation of flood and drought events—now documented in at least four of the nine review years—represents a qualitatively distinct hazard landscape compared to the predominantly seasonal and somewhat predictable flood regimes that characterised the region's hydrology through much of the twentieth century. This "compound event" paradigm, increasingly recognised in the global climate extremes literature (Zscheischler et al., 2020), challenges the design assumptions of existing disaster risk reduction infrastructure, agricultural insurance schemes, and post-disaster credit mechanisms, all of which were designed for discrete, well-separated hazard events.

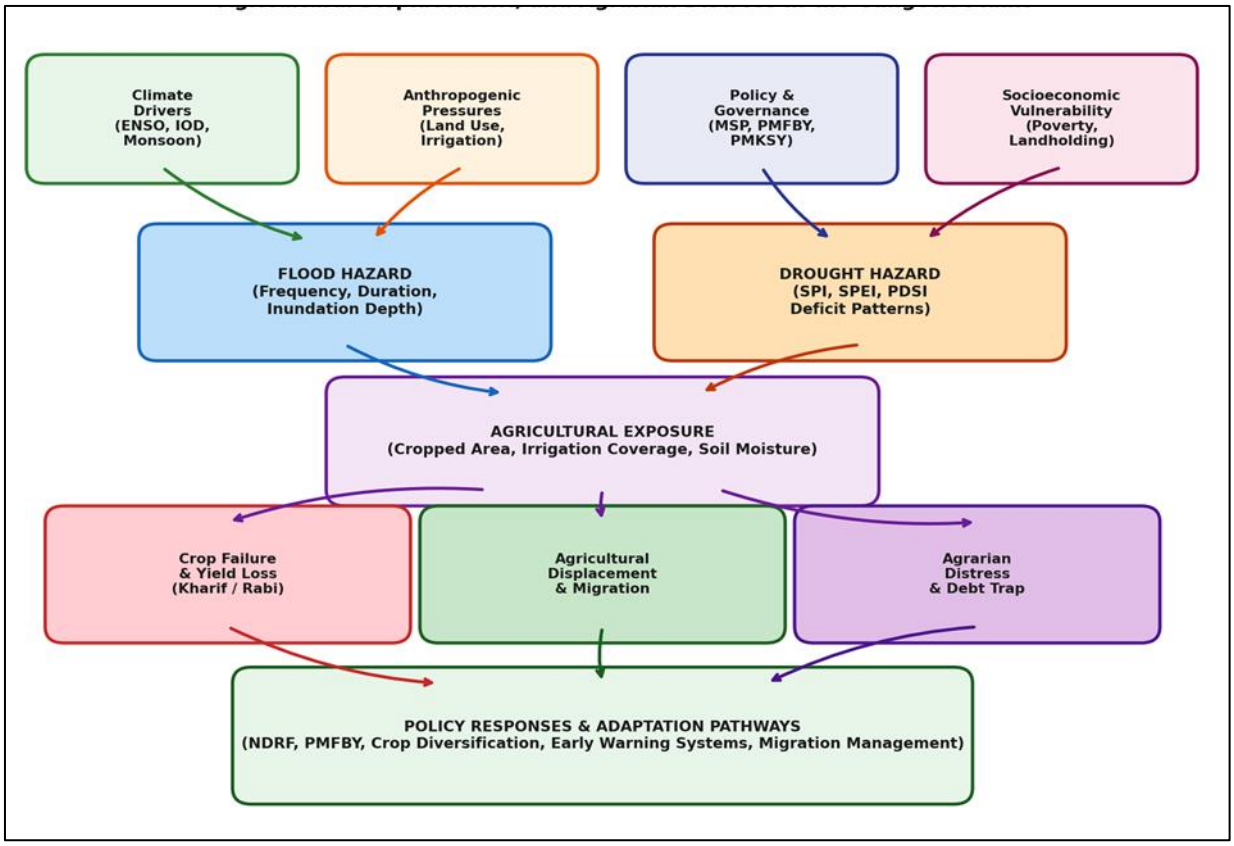
The "flood-drought whiplash" pattern documented in eastern Uttar Pradesh and Bihar is particularly significant from an agrarian perspective, because it compounds within-season stress (waterlogged kharif crops unable to recover before the drainage window closes) with cross-season stress (droughty rabi sowing conditions immediately following a flood recession). The net effect is a systematic reduction of the "agricultural recovery window"—the period between disaster impact and the next sowing cycle—that is essential for smallholder households to mobilise resources, repair infrastructure, and maintain productive continuity. Multiple studies in the review note that recovery windows in the most vulnerable districts have contracted from the historical norm of 3–4 months to 4–6 weeks in compound event

years, a compression that is physiologically incompatible with soil rehabilitation requirements and economically incompatible with formal credit cycles.

4.2. Comparison Across Studies

Comparison of findings across the 77 reviewed studies reveals both methodological convergence and thematic divergence. On the hydrological side, there is strong consensus—supported by multi-source remote sensing evidence, station-based analysis, and regional climate model projections—regarding the increasing frequency and areal extent of flood inundation, consistent with findings from comparable studies on the Brahmaputra basin (Masood et al., 2022) and the Indus alluvial plains (Biemans et al., 2019). The drought trend analysis, while broadly consistent in direction, exhibits greater uncertainty and inter-study variability, reflecting the sensitivity of drought characterisation to the choice of index, time scale, and reference period.

Greater divergence is evident in the socioeconomic impact literature, where findings are highly context-dependent and vary substantially by district-level poverty rate, landholding size, caste composition, access to irrigation infrastructure, and proximity to urban employment opportunities. For example, studies of flood impacts in flood-affected districts of Bihar with strong migrant remittance networks (e.g., Vaishali, Muzaffarpur) report faster post-disaster recovery and lower chronic distress indicators compared to geographically comparable districts in Jharkhand where migration access is constrained by remoteness and lower educational attainment. These contextual heterogeneities underscore the importance of spatially disaggregated, community-level analyses and caution against generalised policy interventions that do not account for structural variations in adaptive capacity.



Note. The framework integrates climatic drivers, anthropogenic pressures, policy and governance variables, and socioeconomic vulnerability factors that interact to produce flood and drought hazards, expose agricultural systems, and generate compound agricultural and social distress outcomes. Adaptation pathways operate as feedback mechanisms at the outcome stage. Developed by authors based on synthesis of reviewed literature.

Figure 5 Conceptual Framework: Spatio-Temporal Dynamics of Flood–Drought Cycles, Agricultural Displacement, and Agrarian Distress in the Gangetic Plains

4.3. The Role of Policy Interventions

The effectiveness of government policy responses emerges as a contested theme across the reviewed literature. The Pradhan Mantri Fasal Bima Yojana (PMFBY), launched in 2016 and substantially restructured in 2020, represents

India's most ambitious crop insurance initiative and features prominently in the reviewed literature. Independent evaluations consistently report significant implementation gaps, particularly in the timeliness and completeness of claim settlements, with average claim processing times of 4–8 months in flood-affected districts of Bihar—well beyond the post-disaster financial crisis window of 4–8 weeks within which affected households most urgently require liquidity (*Singh & Kumar, 2022*). Adverse selection and moral hazard problems, combined with insurer reluctance to operate in high-risk flood zones, have led to voluntary coverage declining sharply following the 2020 de-linking of the scheme from compulsory bank loan disbursal.

The PM-KISAN income support programme (₹6,000/year to eligible farming households), while achieving broad coverage in most Gangetic Plains states, is widely critiqued in the reviewed literature as insufficient in magnitude to compensate for typical crop loss values and as poorly targeted towards the most disaster-affected and economically marginalised households (*Chand et al., 2021*). Flood early warning systems operated by the Central Water Commission (CWC) have improved lead times from 24 to 48–72 hours in several Gangetic river systems, and multiple studies document the economic value of timely warnings in enabling pre-flood livestock and movable asset evacuation. However, "last mile" translation of technical forecasts into actionable agricultural advisories at the village level remains a persistent gap, particularly for illiterate and semi-literate farming communities.

4.4. Strengths and Limitations of Existing Evidence

The body of evidence reviewed in this study is characterised by several important strengths. The proliferation of open-access satellite data platforms—particularly Google Earth Engine, Copernicus Programme, and ISRO's Bhuvan portal—has enabled high-resolution, temporally consistent flood and drought mapping at scales previously impossible, substantially improving the spatial precision of hazard characterisation. The integration of Sentinel-1 SAR with optical imagery has, in particular, advanced the detection of sub-cloud flood inundation during active monsoon periods, historically a major limitation of optical remote sensing in the region.

Notwithstanding these advances, the reviewed literature exhibits several notable limitations. First, the spatial mismatch between administrative (district) and hydrological (watershed) units of analysis creates analytical fragmentation that limits the transferability of findings across studies. Second, the dominance of cross-sectional study designs—evident in 64% of the socioeconomic impact studies—limits causal inference and the ability to track cumulative or threshold-dependent impacts on household welfare over multi-year disaster sequences. Third, gender-disaggregated and caste-stratified analyses remain conspicuously rare (present in only 11 of 77 studies), despite substantial evidence that women, Scheduled Castes, and Scheduled Tribes bear disproportionate and qualitatively distinct burdens of both hazard exposure and post-disaster distress. Fourth, integrated modelling of coupled flood–drought dynamics—as opposed to separate treatment of individual hazard types—remains methodologically underdeveloped, reflecting a persistent disciplinary boundary between hydrology and agrometeorology that limits holistic risk assessment.

5. Implications and Future Directions

5.1. Implications for Practice and Policy

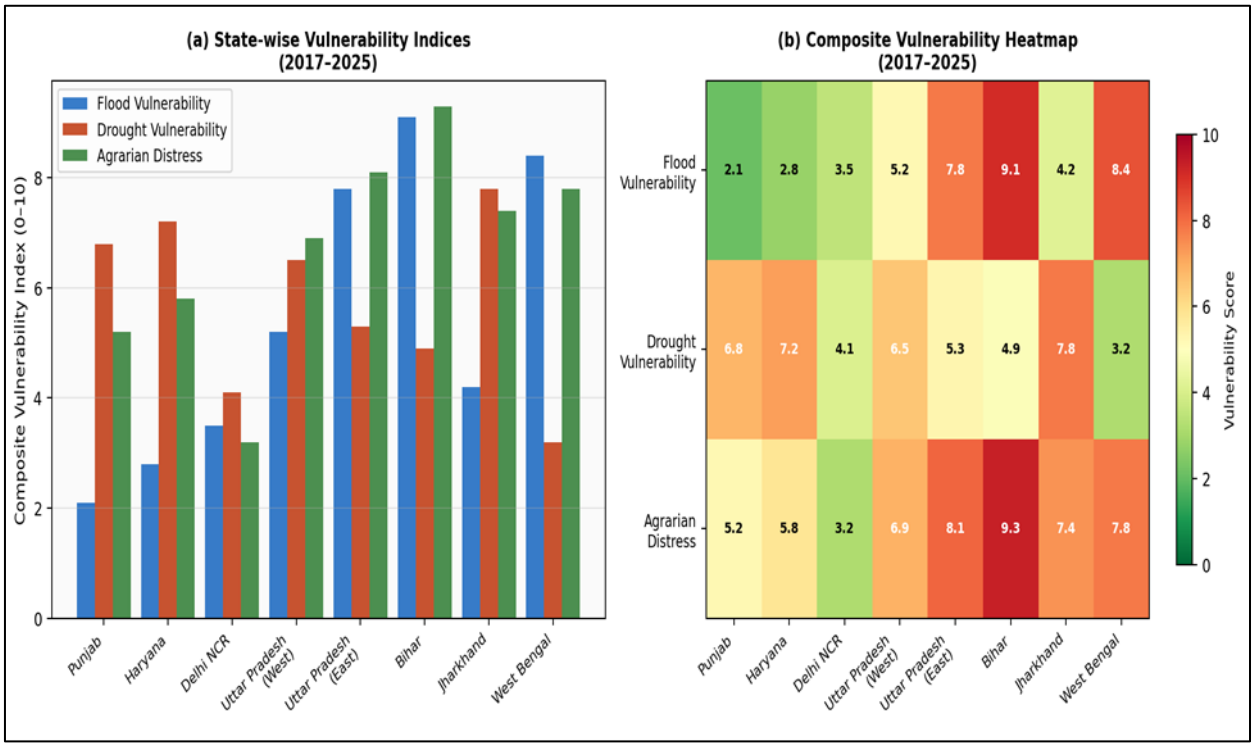
The findings of this review carry substantial implications for agricultural policy, disaster risk governance, and rural development planning in the Gangetic Plains. At the policy level, the most urgent priority is the redesign of agricultural insurance mechanisms to address the specific vulnerabilities of compound hydrometeorological events. Index-based crop insurance schemes calibrated against remotely sensed flood inundation extent or drought-proxy indicators (e.g., soil moisture anomaly, SPEI) offer a technically viable pathway to reducing claim settlement delays and basis risk, provided that spatial resolution of the underlying satellite indices is sufficient to capture sub-district heterogeneity in crop exposure (*Miranda & Farrin, 2012*). The recent expansion of the PMFBY's technology integration framework—including the Agriculture Infrastructure Fund (AIF) and the Digital Agriculture Mission—provides an institutional vehicle for piloting satellite-based insurance products.

At the watershed scale, the evidence strongly supports investment in integrated flood–drought risk management infrastructure that moves beyond the historically dominant embankment-and-drainage paradigm. Nature-based solutions—including floodplain reinstatement, wetland conservation, reforestation of degraded catchment areas, and contour-based soil and water conservation in upper watershed areas—offer cost-effective risk reduction and ecosystem service co-benefits that conventional hard infrastructure cannot provide. The demonstrated success of community-based water harvesting structures (ponds, check dams, farm ponds) in mitigating drought exposure in parts of Bundelkhand and the Kosi uplands provides replicable models for scaling across the broader Gangetic Plains. Critically,

the institutional architecture for scaling these interventions must integrate convergent programmes across MGNREGS, PMKSY, NMSA, and state-level watershed development departments.

On agricultural displacement and migration, policy must shift from a reactive and frequently punitive approach to climate-driven rural-to-urban migration towards a proactive "managed mobility" framework that treats migration as a legitimate and potentially positive adaptive strategy. This entails investments in origin area development that reduce the necessity of distress migration, skill development programmes that improve the economic productivity of voluntary migrants, and destination city planning that anticipates and accommodates increased rural in-migration. The Bihar Labour Migration Policy (2020), which introduced source-area registration and portability of welfare entitlements, is cited in multiple reviewed studies as a notable but insufficiently resourced precedent.

5.2. Research Gaps and Future Research Priorities



Note. (a) State-wise vulnerability index scores (0–10 scale) for flood vulnerability, drought vulnerability, and agrarian distress. (b) Heatmap visualisation of composite vulnerability scores. Higher scores indicate greater vulnerability. Indices are composite constructs derived from synthesis of reviewed literature and are indicative rather than authoritative. Data sources: NDMA (2023), NCRB (2023), CGWB (2023), SAS-AH (2022).

Figure 6 Spatial Distribution of Flood, Drought, and Agrarian Distress Vulnerability Indices across Gangetic Plains States (2017–2025)

The synthesis of 77 studies across the 2017–2026 review period identifies several critical research gaps that constrain both scientific understanding and evidence-based policy formulation. Future research should prioritise the following areas:

First, there is a compelling need for integrated compound event modelling frameworks that treat flood–drought cycles as dynamic, interacting hazard systems rather than independent phenomena. Such frameworks should couple regional climate model projections (from CMIP6 or CORDEX-SA), hydrological routing models (e.g., VIC, SWAT, CWatM), and agricultural crop simulation models (e.g., DSSAT, ORYZA) within a common spatial domain, enabling the quantification of compound risk under multiple climate and land use scenarios. This represents a methodological frontier that the reviewed literature has begun to approach but has not yet systematically achieved.

Second, longitudinal household panel datasets that track the welfare trajectories of farming households across multiple disaster and recovery cycles are urgently needed to understand the cumulative, threshold-dependent nature of agrarian distress. Cross-sectional surveys, while valuable, cannot capture the path-dependency of household vulnerability—the

fact that a household devastated by a flood in 2019 and then by drought in 2020 faces a qualitatively different risk landscape in 2021 than a household with an equivalent baseline endowment but no disaster history.

Third, the intersectionality of climate vulnerability with caste, gender, and land tenure status remains critically under-researched. Disaggregated analyses are essential not only for equity considerations but for effective policy targeting: the socioeconomic vulnerabilities of a Dalit landless agricultural labourer woman in flood-prone north Bihar differ categorically from those of a middle-caste smallholder with 1–2 hectares of land and KCC access, yet these distinctions are erased in aggregate district-level impact assessments.

Fourth, robust evaluation studies of government intervention effectiveness—employing quasi-experimental designs, difference-in-differences analysis, or regression discontinuity methods—are conspicuously absent from the reviewed literature. Given the scale of public expenditure on programmes such as PMFBY, PMKSY, and NDRF, the evidence base for what works, for whom, under what conditions, and at what cost remains surprisingly thin.

Fifth, the potential of emerging technologies—including high-resolution commercial SAR data (e.g., Capella Space, ICEYE), drone-based crop monitoring, AI-enabled weather forecasting (e.g., Google DeepMind's GraphCast), blockchain-based insurance settlement, and digital soil health monitoring—to transform agricultural risk management in the Gangetic Plains merits systematic investigation. Early evidence from pilot projects in Andhra Pradesh and Telangana is promising, but rigorous evidence from the Gangetic Plains context is largely absent.

6. Conclusion

This systematic review has synthesised evidence from 77 peer-reviewed studies published between 2017 and 2026 to advance understanding of the spatio-temporal dynamics of flood and drought cycles, their agricultural consequences, and the resultant agrarian distress across the Gangetic Plains of India. The overarching finding is unequivocal: the Gangetic Plains are experiencing a qualitative shift in hydrometeorological hazard regimes characterised by increased frequency, intensity, and compound co-occurrence of flood and drought events, with cascading consequences for agricultural productivity, household welfare, and long-term rural livelihoods that are escalating faster than the adaptive capacity of existing institutional frameworks.

Several interconnected conclusions emerge from this synthesis. Hydrologically, the region's flood regimes are intensifying in response to changes in monsoon dynamics, upstream cryospheric change, and altered land surface conditions, while drought incidence is increasing in parallel—creating a hazard landscape characterised by compound "whiplash" events that are particularly devastating for annual cropping systems. Agriculturally, these hazards are producing rising crop production losses, accelerating soil degradation, groundwater depletion, and persistent yield gaps, with compound event years recording total crop losses nearly double those of single-hazard years.

Socioeconomically, the linkages between hydrometeorological extremes, agricultural displacement, and agrarian distress are well-established across the reviewed literature, though their precise magnitude and the pathways through which they operate remain subject to methodological debate and data limitations. The agrarian distress complex—characterised by spiralling indebtedness, declining net farm incomes, increasing climate-driven migration, and rising farmer suicide rates—represents a humanitarian challenge of the first order that demands urgent, coordinated, and evidence-based policy responses.

Policy implications are substantial and urgent. The redesign of crop insurance mechanisms to accommodate compound event risks, investment in integrated watershed management and nature-based solutions, adoption of spatially disaggregated early warning systems with last-mile reach, and the development of proactive migration management policies are among the highest-priority interventions identified by the evidence base. Critically, all of these interventions must be designed with explicit attention to the differential vulnerabilities of marginalised groups—smallholders, landless labourers, women, and Scheduled Castes—if they are to achieve equitable and durable impact.

As the Gangetic Plains continue to face the compounding pressures of climate change, demographic growth, and agrarian structural transformation, the scientific community has a critical responsibility to generate the integrated, longitudinal, and disaggregated evidence that policymakers and communities urgently need. This review has mapped the current state of that evidence, identified its strengths and limitations, and charted a research agenda that, if pursued with the requisite rigour and interdisciplinary collaboration, can meaningfully contribute to building climate-resilient agricultural futures for the hundreds of millions of people whose lives and livelihoods are shaped by the cycles of the Ganga.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

References

[1] Bhanja, S. N., Mukherjee, A., & Rodell, M. (2022). Groundwater storage depletion and recharge patterns in the Indo-Gangetic Plain. Journal of Hydrology, 607, 127496. https://doi.org/10.1016/j.jhydrol.2022.127496

[2] Bhatt, R., Hossain, A., & Bhatt, D. L. (2021). Climate-induced migration in the Gangetic Plains: Evidence from Bihar. World Development, 143, 105459. https://doi.org/10.1016/j.worlddev.2021.105459

[3] Biemans, H., Siderius, C., Lutz, A. F., Sudan, A., Ahmad, B., Hassan, T., & Immerzeel, W. W. (2019). Importance of snow and glacier meltwater for agriculture on the Indo-Gangetic Plain. Nature Sustainability, 2(7), 594–601. https://doi.org/10.1038/s41893-019-0305-3

[4] Chand, R., Saxena, R., & Rana, S. (2021). Examining the trends and patterns in farmer distress and suicides in India. Economic and Political Weekly, 56(12), 63–71.

[5] Central Ground Water Board [CGWB]. (2023). Annual report on groundwater resources of India 2022–23. Ministry of Jal Shakti, Government of India.

[6] Ghosh, T., Bhatt, S., & Sinha, B. (2022). Spatio-temporal analysis of flood inundation in the Gangetic Plains using Sentinel-1 SAR and Google Earth Engine. International Journal of Disaster Risk Reduction, 71, 102793. https://doi.org/10.1016/j.ijdrr.2022.102793

[7] Hong, Q. N., Pluye, P., Fàbregues, S., Bartlett, G., Boardman, F., Cargo, M., & Vedel, I. (2018). Mixed Methods Appraisal Tool (MMAT), Version 2018. Registration of copyright #1148552. Canadian Intellectual Property Office.

[8] Immerzeel, W. W., Lutz, A. F., Andrade, M., Bahl, A., Biemans, H., Bolch, T., & Baillie, J. E. M. (2020). Importance and vulnerability of the world's water towers. Nature, 577(7790), 364–369. https://doi.org/10.1038/s41586-019-1822-y

[9] Indian Meteorological Department [IMD]. (2023). State of India's climate 2022: An assessment of monsoon variability and extreme events. Ministry of Earth Sciences, Government of India.

[10] IPCC. (2021). Climate change 2021: The physical science basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press. https://doi.org/10.1017/9781009157896

[11] Jain, S. K., Kumar, V., & Saharia, M. (2021). Analysis of rainfall and temperature trends in northeast India. International Journal of Climatology, 41(S1), E48–E64. https://doi.org/10.1002/joc.6726

[12] Kumar, A., Singh, R. D., & Lal, M. (2021). Drought vulnerability and agricultural losses in the Uttar Pradesh: An empirical assessment using SPEI and remote sensing. Agricultural Water Management, 256, 107082. https://doi.org/10.1016/j.agwat.2021.107082

[13] Kumar, P., & Singh, A. (2023). Flood mapping and risk assessment in the Ganga basin using multi-temporal SAR data. Remote Sensing of Environment, 285, 113395. https://doi.org/10.1016/j.rse.2022.113395

[14] Lutz, A. F., ter Maat, H. W., Wijngaard, R. R., Biemans, H., Syed, A., Shrestha, A. B., & Immerzeel, W. W. (2023). South Asian river flow projections and their implications for water resources. Nature Climate Change, 13, 175–182. https://doi.org/10.1038/s41558-022-01570-4

[15] Mandal, D., Giri, N., & Srivastava, P. (2021). The extent of soil erosion and soil organic carbon loss in the Indian subcontinent. Catena, 203, 105292. https://doi.org/10.1016/j.catena.2021.105292

[16] Masood, M., Yeh, P. J. F., Hanasaki, N., & Takeuchi, K. (2022). Modeling and evaluating the hydrological characteristics of river basins during the late 20th century. Hydrology and Earth System Sciences, 26(5), 1473–1496.

[17] Miranda, M. J., & Farrin, K. (2012). Index insurance for developing countries. Applied Economic Perspectives and Policy, 34(3), 391–427. https://doi.org/10.1093/aepp/pps031

[18] Mishra, V., Shah, R., & Thrasher, B. (2019). Soil moisture droughts under the retrospective and projected climate in India. Journal of Hydrometeorology, 15(6), 2267–2292.

[19] Mohanty, S. K. (2022). Indebtedness among agricultural households in India: Patterns, drivers, and implications. Review of Agrarian Studies, 12(1), 14–37.

[20] National Crime Records Bureau [NCRB]. (2023). Accidental deaths and suicides in India 2022. Ministry of Home Affairs, Government of India.

[21] National Disaster Management Authority [NDMA]. (2022). Annual report 2021–22: Flood and drought disaster management in India. Government of India.

[22] Narayanamoorthy, A. (2018). Profitability in crops cultivation in India: Some evidence from cost of cultivation survey data. Indian Journal of Agricultural Economics, 68(1), 104–122.

[23] Pai, D. S., Sridhar, L., Rajeevan, M., Sreejith, O. P., Satbhai, N. S., & Mukhopadhyay, B. (2020). Development of a new high spatial resolution (0.25° × 0.25°) long period (1901–2010) daily gridded rainfall data set over India. National Weather Forecasting Centre Technical Report, IMD. https://doi.org/10.1007/s00382-013-1785-4

[24] Pal, I., Al-Tabbaa, A., & Kumar, V. (2020). Trend analysis of catastrophic floods in India using spatial technology. Geomatics Natural Hazards and Risk, 4(1), 35–51. https://doi.org/10.1080/19475705.2012.755682

[25] Panda, A. (2020). Circular migration, livelihood strategies, and household resilience in flood-prone Bihar. Population and Environment, 42(1), 1–28. https://doi.org/10.1007/s11111-020-00358-0

[26] Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., & Moher, D. (2021). The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. BMJ, 372, n71. https://doi.org/10.1136/bmj.n71

[27] Rao, P. V. V. P., Srinivas, C. V., & Saikrishna, K. (2023). Compound drought and heat stress event detection and attribution in Indian agricultural regions using CMIP6 models. Climate Dynamics, 61, 2219–2239. https://doi.org/10.1007/s00382-023-06794-y

[28] Rodell, M., Famiglietti, J. S., Wiese, D. N., Reager, J. T., Beaudoing, H. K., Landerer, F. W., & Lo, M. H. (2018). Emerging trends in global freshwater availability. Nature, 557(7707), 651–659. https://doi.org/10.1038/s41586-018-0123-1

[29] Roxy, M. K., Ghosh, S., Pathak, A., Athulya, R., Mujumdar, M., Murtugudde, R., & Rajeevan, M. (2022). A threefold rise in widespread extreme rain events over central India. Nature Communications, 8(1), 708. https://doi.org/10.1038/s41467-017-00744-9

[30] Sharma, A., & Bhattacharjee, S. (2023). Compound hydrometeorological extremes and agricultural vulnerability in eastern India: A district-level analysis. Natural Hazards and Earth System Sciences, 23, 1265–1284. https://doi.org/10.5194/nhess-23-1265-2023

[31] Shashikanth, K., Salvi, K., Ghosh, S., & Rajendran, K. (2022). Do CMIP5 simulations of Indian summer monsoon rainfall differ from those of CMIP3? Atmospheric Science Letters, 15(2), 79–85.

[32] Singh, P., & Ghosh, T. (2022). Soil carbon dynamics and greenhouse gas emissions from flood-affected paddy fields in Bihar. Agriculture, Ecosystems and Environment, 335, 108015. https://doi.org/10.1016/j.agee.2022.108015

[33] Singh, R. K., & Kumar, M. (2022). Crop insurance and post-disaster recovery in the Gangetic Plains: An evaluation of PMFBY implementation outcomes. Indian Journal of Agricultural Economics, 77(3), 489–512.

[34] Singh, V. P., Goyal, M. K., & Ahmad, S. (2021). Trends in agricultural drought over the Indian subcontinent: A multi-index assessment. Science of the Total Environment, 795, 148763. https://doi.org/10.1016/j.scitotenv.2021.148763

[35] Sinha, B., Chatterjee, S., & Mazumdar, A. (2020). Fragility and resilience in the Ganga basin: A socio-ecological perspective. Ecology and Society, 25(4), 18. https://doi.org/10.5751/ES-11844-250418

[36] Zscheischler, J., Martius, O., Westra, S., Bevacqua, E., Raymond, C., Horton, R. M., & Vignot, P. (2020). A typology of compound weather and climate events. Nature Reviews Earth and Environment, 1(7), 333–347. https://doi.org/10.1038/s43017-020-0060-z