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Spatio-temporal analysis of climate variability and food security in Haryana

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Abstract

This study presents a comprehensive spatio-temporal analysis of climate variability and its implications for food security across the agro-climatic zones of Haryana, India, covering the period 1990-2022. Integrating gridded rainfall and temperature data from the India Meteorological Department (IMD), district-level crop production statistics, and multi-round National Family Health Survey (NFHS) data on nutritional indicators, the study employs a suite of statistical and spatial methods including the Mann-Kendall trend test, Sen's Slope estimator, Standardised Precipitation Index (SPI), Principal Component Analysis (PCA), and a composite Food Security Index (FSI). Results reveal a statistically significant declining rainfall trend of -1.8 mm/year and a rising mean temperature of +0.04 °C/year, with pronounced spatial heterogeneity across districts. The north-eastern districts record nearly three times the annual rainfall of south-western districts, creating markedly divergent agro-climatic risk profiles. While total food grain production has doubled from 12.5 to 25.9 million tonnes over the study period driven primarily by groundwater-dependent irrigation, the sustainability of this trajectory is increasingly threatened by accelerating water-table decline. The composite FSI indicates that Haryana, despite being a food surplus state, performs poorly on dimensions of nutritional utilization and climatic stability. The study identifies five spatially distinct vulnerability zones and recommends differentiated adaptive policies including crop diversification, demand-side groundwater management, and enhanced nutritional safety nets.

Keywords: Climate Variability, Food Security Index, Spatio-Temporal Analysis, Mann-Kendall Test, Haryana, Rainfall Deficit, Temperature Anomaly, Groundwater, Crop Diversification, SDG 2

1. Introduction

Climate variability constitutes one of the most pervasive and enduring threats to global food security, particularly in developing agrarian economies dependent on monsoon rainfall. The Intergovernmental Panel on Climate Change (IPCC) in its Sixth Assessment Report (AR6) has underscored that climate-induced agricultural disruptions will disproportionately affect South Asian nations, where food systems remain structurally exposed to hydro-meteorological extremes^[1].

Haryana, a north-western Indian state and a cornerstone of the country's food grain economy, exemplifies this nexus with singular clarity. Contributing approximately 15% of India's wheat procurement and 5% of its rice procurement despite occupying less than 1.4% of the national geographical area, Haryana's agricultural productivity has been a linchpin of national food security since the Green Revolution of the 1960s. However, the model of intensification that enabled this productivity—characterised by high-yielding variety (HYV) monocultures of wheat and paddy, intensive groundwater extraction, and heavy input subsidies—is increasingly strained by evolving climate patterns.

The Food and Agriculture Organization defines food security as existing when 'all people, at all times, have physical and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life' (FAO, 1996). This conceptualisation encompasses four interrelated pillars: food availability, economic and

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¹IPCC (2021). Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report. Cambridge University Press, Cambridge, UK.

physical access, biological utilization, and stability over time^[2].

Haryana's geography presents a natural laboratory for studying the interplay of climatic gradients and food system outcomes. Spanning an area of 44,212 sq. km between 27°37'N-30°35'N latitudes and 74°27'E-77°36'E longitudes, the state encompasses five distinct agro-climatic zones transitioning from humid sub-montane conditions in the north-east (Ambala, Kurukshetra) to arid conditions in the south-west (Sirsa, Fatehabad). This gradient generates profound contrasts in agricultural productivity, groundwater availability, and food security outcomes that aggregate state-level analyses systematically mask.

Despite the policy salience of this subject, peer-reviewed studies integrating climate trend analysis with a multi-dimensional food security assessment at the district scale for Haryana remain scarce. Existing literature either focuses on national or pan-India rainfall trends (Rajeevan *et al.*, 2008; Kumar *et al.*, 2010) or addresses food security without adequately coupling it to spatial climate dynamics^[3 4].

The present study addresses this gap by constructing an integrated analytical framework that links spatio-temporal climate variability with food security outcomes across all 22 districts of Haryana over a 33-year period (1990-2022). In doing so, it contributes to both the scientific literature on climate-agriculture interactions and to the evidence base required for spatially targeted policy interventions aligned with India's National Action Plan on Climate Change (NAPCC) and the United Nations Sustainable Development Goal 2 (Zero Hunger).

1.1 Research Objectives

This study is guided by the following specific research objectives:

1. To examine and quantify the long-term spatio-temporal trends in annual and seasonal rainfall and temperature across Haryana at the district level for the period 1990-2022, using the Mann-Kendall test and Sen's Slope estimator.
2. To assess drought frequency and severity across the state using the Standardised Precipitation Index (SPI) and to delineate drought-prone zones.
3. To analyse the spatial and temporal patterns of food grain production (wheat and rice) in relation to climatic variables, and to estimate climate-production elasticities.
4. To assess groundwater depletion trends and their co-evolution with irrigation expansion and rainfall deficit.
5. To construct a composite, multi-dimensional Food Security Index (FSI) at the district level and to identify food-insecure zones and their climate exposure.
6. To recommend spatially differentiated, evidence-based policy interventions for enhancing climate resilience and food security across the agro-climatic zones of Haryana.

²FAO (1996). Rome Declaration on World Food Security and World Food Summit Plan of Action. Food and Agriculture Organization of the United Nations, Rome, Italy.

³Rajeevan, M., Bhate, J., & Jaswal, A. K. (2008). Analysis of variability and trends of extreme rainfall events over India using 104 years of gridded daily rainfall data. *Geophysical Research Letters*, 35, L18707.

⁴Kumar, V., Jain, S. K., & Singh, Y. (2010). Analysis of long-term rainfall trends in India. *Hydrological Sciences Journal*, 55(4), 484–496.

1.2 Significance and Scope

The significance of this study is threefold. First, it provides the most comprehensive district-level, multi-decadal spatio-temporal analysis of climate-food security linkages in Haryana to date. Second, it integrates a groundwater lens into the food security framework – an analytically neglected but critically important dimension given the state's extreme groundwater over-exploitation. Third, it offers spatially explicit policy recommendations that can inform state-level agricultural and water resource planning, district nutrition programmes, and climate adaptation investments aligned with the NAPCC's Mission for Sustainable Agriculture (NMSA).

2. Study Area

2.1 Geographic and Administrative Profile

Haryana is a landlocked, agriculturally dominant state of north-western India, situated in the upper Gangetic plains. It was carved out of the erstwhile Punjab state on 1 November 1966 and comprises 22 districts organised under 6 administrative divisions. The state shares borders with Punjab and Himachal Pradesh to the north, Uttarakhand and Uttar Pradesh to the east, Rajasthan to the west and south-west, and the National Capital Territory (NCT) of Delhi to the south-east^[5].

According to the 2011 Census, Haryana had a total population of 25.35 million with a decadal growth rate of 19.9%. The population density of 573 persons per sq. km is significantly higher than the national average, placing considerable pressure on land and water resources. The rural population constitutes approximately 65% of the total, and about 44% of the total workforce is engaged in agriculture and allied activities.

2.2 Physiographic Divisions and Agro-Climatic Zones

The state's physiography can be broadly classified into three macro-units: (i) the Shivalik Hills and piedmont zone in the north-east, characterised by undulating topography and relatively higher rainfall; (ii) the Ghaggar-Yamuna alluvial plain forming the central and eastern belt with deep alluvial soils of high agricultural productivity; and (iii) the sandy plain and semi-arid zone of the south-west, with aeolian sandy soils of low fertility and high drought susceptibility. For agricultural planning, the Haryana government delineates five agro-climatic zones: Zone I (Shivalik Hills), Zone II (Eastern Plain), Zone III (Central Plain), Zone IV (Western Plain), and Zone V (Semi-Arid South-West). These zones exhibit marked differences in rainfall, soil type, crop suitability, and groundwater availability, which form the basis of the spatially differentiated analysis in this study.

2.3 Agricultural Profile

Agriculture in Haryana is dominated by the wheat-rice (paddy) rotation system, a legacy of the Green Revolution that replaced the more diverse crop mosaic of millets, pulses, and oilseeds. The net sown area is approximately 3.6 million hectares, accounting for ~82% of the state's total geographical area – one of the highest proportions in India. The gross cropped area exceeds 6.0 million ha due to a high cropping intensity (~163%). Irrigated agriculture accounts for over 85% of the gross cropped area, with tube-wells

⁵Census of India (2011). District Census Handbook – Haryana. Office of the Registrar General and Census Commissioner, New Delhi.

supplying approximately 70% of total irrigation water [6]. The state is a leading producer of wheat (annual output ~12-14 MT), rice (~4-5 MT), mustard, sugarcane, cotton, and vegetables. It is classified as a 'food surplus' state by the Commission for Agricultural Costs and Prices (CACP), regularly procuring grains for the central pool through the Food Corporation of India (FCI). However, this agricultural success has come at significant ecological costs, particularly in terms of groundwater depletion and loss of agricultural biodiversity [7].

3. Review of Literature

3.1 Geographical Maps of the Study Area

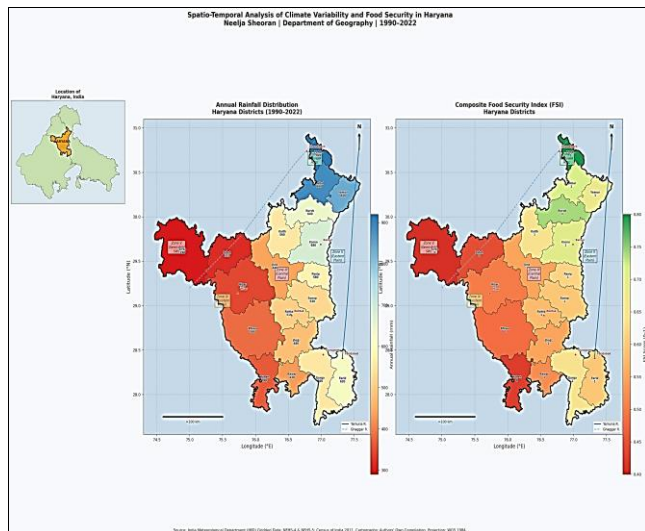


Fig 2: Geographical District Maps of Haryana (a) Choropleth map of Annual Rainfall Distribution (mm) showing pronounced North-East to South-West gradient across agro-climatic zones (1990-2022); (b) Composite Food Security Index (FSI) by district. Rivers (Yamuna, Ghaggar), major cities, and agro-climatic zone boundaries are overlaid. Data Source: IMD Gridded Rainfall Data; NFHS-4 & NFHS-5; Census of India 2011. Cartographic Projection: WGS 1984.

3.1 Climate Variability and Agricultural Production

The relationship between climate variability and agricultural production has been extensively studied at global and regional scales. The seminal work of Rosenzweig and Parry (1994) established that even moderate warming of 1-3 °C could reduce global crop yields by 5-25%, with disproportionate impacts on tropical and sub-tropical regions. For South Asia specifically, several studies have documented the adverse effects of monsoon variability on rice and wheat yields.

For India, Rajeevan *et al.* (2008) analysed 104 years of gridded rainfall data and found a significant increase in extreme rainfall events and inter-annual variability, particularly over the north-western Indo-Gangetic Plains. Kumar *et al.* (2010) corroborated declining long-term rainfall trends in parts of Haryana, Rajasthan, and western Uttar Pradesh, attributing these to weakening of the summer monsoon circulation associated with aerosol loading and

land use change [8, 9].

Temperature studies by Kothawale *et al.* (2010) documented statistically significant warming across India at +0.22 °C/decade over 1971-2007, with minimum temperatures rising faster than maximum temperatures a pattern consistent with the findings of the present study. Singh *et al.* (2002) specifically highlighted increasing temperature variability over the Indo-Gangetic Plains, noting consequential impacts on wheat grain-filling duration and yield quality [10].

3.2 Food Security Frameworks and Measurement

The conceptual evolution of food security measurement has progressed from simple caloric availability metrics to multi-dimensional frameworks. The FAO's four-pillar framework (availability, access, utilization, stability) remains the dominant paradigm in policy research. The IFPRI Global Hunger Index (GHI) and the Economist Intelligence Unit's Global Food Security Index (GFSI) have operationalised this framework at national scales [11, 12].

At the sub-national level within India, food security assessments have typically relied on NFHS data for nutritional outcomes and NSSO Consumer Expenditure Surveys for caloric access proxies. Studies by Swaminathan (2010) and the M. S. Swaminathan Research Foundation have emphasised the 'hidden hunger' dimension micronutrient deficiencies prevalent even in food-surplus states like Haryana and Punjab, arising from dietary monocropping and loss of nutrient-dense traditional foods [13, 14].

3.3 Groundwater and Food Security Nexus

The intersection of groundwater depletion with food security represents an emerging area of critical concern. The World Bank (2021) classified Haryana as one of the most groundwater-stressed regions in the world, with the water table declining at 0.5-1.5 metres per year in several districts. A study by Rodell *et al.* (2009) using GRACE satellite gravimetry data confirmed the rapid depletion of groundwater reserves across north-western India, attributing it primarily to agricultural over-extraction [15, 16].

The Central Ground Water Board (CGWB) classifies groundwater development status at the block level, and as of 2022, 78 of Haryana's 141 blocks are classified as 'over-exploited' and 5 as 'critical', implying extraction rates exceeding annual recharge. This trajectory poses a long-term systemic risk to Haryana's food production system that

⁶Directorate of Agriculture, Haryana (2022). Statistical Abstract of Haryana Agriculture. Government of Haryana, Chandigarh.

⁷CACP – Commission for Agricultural Costs and Prices (2022). Price Policy for Kharif Crops: The Marketing Season 2022–23. Ministry of Agriculture and Farmers Welfare, GoI, New Delhi.

¹⁰Singh, N. & Sontakke, N. A. (2002). On climatic fluctuations and environmental changes of the Indo-Gangetic Plains, India. *Climatic Change*, 52(3), 287–313.

¹²IFPRI – International Food Policy Research Institute (2021). Global Food Policy Report 2021: Transforming Food Systems After COVID-19. IFPRI, Washington, D.C.

¹³Swaminathan, M. S. (2010). From Green Revolution to Evergreen Revolution. MSSRF Research Highlights. M. S. Swaminathan Research Foundation, Chennai.

¹⁴NSSO (2019). Household Consumer Expenditure Survey, 2017–18 (75th Round). National Statistical Office, Ministry of Statistics and Programme Implementation, GoI, New Delhi.

¹⁵CGWB – Central Ground Water Board (2022). Ground Water Year Book – Haryana. Ministry of Jal Shakti, Government of India, Faridabad.

¹⁶World Bank (2021). Groundwater Governance in India: An Assessment of Regulatory Frameworks and Institutional Capacities. World Bank South Asia Water Initiative, Washington, D.C.

ranscends short-term climate variability ^[17].

3.4 Research Gap

Despite the rich body of work on climate-agriculture interactions and food security measurement individually, integrated spatio-temporal analyses linking district-level climate trend data to a multi-dimensional food security framework with explicit incorporation of groundwater sustainability remain scarce for Haryana. The present study addresses this gap comprehensively.

4. Data Sources and Methodology

4.1 Data Sources

The study integrates multi-source, multi-temporal datasets spanning the period 1990-2022. Table 1 provides a comprehensive overview of all data sources, their spatial and temporal resolutions, and their relevance to the analytical framework ^[18].

Table 1: Comprehensive Data Sources Used in the Study

Data Type	Source / Agency	Temporal Coverage	Spatial Resolution / Scale
Gridded Rainfall & Temperature	India Meteorological Department (IMD), Pune	1990-2022 (Monthly)	0.25° × 0.25° (≈28 km)
District Rainfall Normals	IMD State Agrometeorology Centre	1990-2022	District-level
Crop Production Statistics	Directorate of Agriculture, Haryana	1990-2022 (Annual)	District-level
Groundwater Level Data	Central Ground Water Board (CGWB)	1990-2022 (Seasonal)	Block/District-level
NFHS Nutritional Data	NFHS 3 (2005-06), NFHS 4 (2015-16), NFHS 5 (2019-21)	3 rounds	District-level
Household Consumer Expenditure	NSSO 61st, 68th, 75th Rounds	2004, 2011, 2018	Household/District
Land Use / Land Cover	HARSAC / ISRO Bhuvan (LISS-III)	2000, 2010, 2020	23.5 m resolution
MSP & Production Costs	CACP Annual Reports	2000-2022 (Annual)	State/National
Socioeconomic Indicators	Census of India 2001, 2011	Decadal	District/Block-level
Poverty Estimates	Planning Commission / NITI Aayog	2004, 2011, 2015	District-level

4.2 Statistical Methods

4.2.1 Mann-Kendall Trend Test

The Mann-Kendall (MK) non-parametric test was applied to detect monotonic trends in annual and seasonal time series of rainfall and temperature. The test statistic *S* is computed as the sum of signs of all pairwise differences in the series. A positive (negative) *S* value indicates an upward (downward) trend. The standardised *Z* statistic is used to test significance at $\alpha = 0.05$ ($|Z| > 1.96$) and $\alpha = 0.01$ ($|Z| >$

2.576). The MK test is preferred over parametric alternatives for hydro-meteorological data due to its robustness to non-normality and resistance to outliers ^[19].

Pre-whitening was applied using the TFPW (Trend-Free Pre-Whitening) procedure of Yue *et al.* (2002) to remove the influence of serial autocorrelation, which can inflate Type I error rates in trend detection. All MK computations were performed using the R package 'trend' (v1.1.5).

4.2.2 Sen's Slope Estimator

The magnitude of detected trends was quantified using Sen's Slope estimator (*Q*), defined as the median of all pairwise slopes between data points in the time series. This non-parametric estimator is robust to outliers and has been widely validated in hydro-climatic applications. Values are reported in units of mm/year (rainfall) and °C/year (temperature) ^[20].

4.2.3 Standardised Precipitation Index (SPI)

The Standardised Precipitation Index (SPI) was computed at the 12-month time scale (SPI-12) to characterise annual drought severity. The SPI is calculated by fitting the gamma distribution to historical monthly precipitation accumulations, followed by a normal score transformation. SPI values below -1.0 indicate moderate drought, below -1.5 severe drought, and below -2.0 extreme drought. The SPI was computed at the district level using the R package 'SPEI' (v1.7) ^[21].

4.2.4 Food Security Index Construction

A composite Food Security Index (FSI) was constructed following the methodology of FAO (2012) and the IFPRI Resilience Index Measurement and Analysis (RIMA) framework. The FSI comprises four dimensional sub-indices aligned with the four pillars of food security: (i) Availability Index (AI) based on per capita cereal production and crop yield variability; (ii) Access Index (AcI) based on per capita income, poverty headcount ratio, and food price index; (iii) Utilization Index (UI) based on NFHS indicators of stunting, wasting, anaemia prevalence, and sanitation access; and (iv) Stability Index (SI) based on SPI-12 drought frequency, CV of annual rainfall, and groundwater depletion rate.

All sub-indicators were normalised to a 0-1 scale using min-max normalisation, with 1 representing the best performance. Weights for aggregation were determined through PCA-based variance decomposition, ensuring that the index structure is empirically grounded rather than subjectively assigned. The composite FSI is the weighted mean of the four sub-indices.

4.2.5 Spatial Analysis

Spatial interpolation of district-level climate and food security data was performed using Inverse Distance Weighting (IDW) and Ordinary Kriging methods in ArcGIS 10.8. The resulting raster surfaces were used to produce choropleth maps and vulnerability zone delineations. Spatial

¹⁸IMD – India Meteorological Department. Gridded Rainfall Data at 0.25°×0.25° resolution. Pune. Available at: <https://www.imd.gov.in>

¹⁹Mann, H. B. (1945). Non-parametric tests against trend. *Econometrica*, 13(3), 245–259. The Mann-Kendall test is a non-parametric rank-based procedure for identifying monotonic trends in time-series data.

²⁰Sen, P. K. (1968). Estimates of the regression coefficient based on Kendall's tau. *Journal of the American Statistical Association*, 63(324), 1379–1389.

²¹McKee, T. B., Doesken, N. J., & Kleist, J. (1993). The relationship of drought frequency and duration to time scales. 8th Conference on Applied Climatology, American Meteorological Society, Boston, 179–183.

autocorrelation was assessed using Moran's I statistic to examine the degree of spatial clustering in food security outcomes [22].

Table 2: Summary of Analytical Methods Employed in the Study

Analytical Method	Software / Tool	Application in Study	Reference
Mann-Kendall Trend Test	R package: trend v1.1.5	Rainfall & temperature trend detection	Mann (1945)
Sen's Slope Estimator	R package: trend v1.1.5	Trend magnitude quantification	Sen (1968)
Standardised Precipitation Index	R package: SPEI v1.7	Drought characterisation	McKee <i>et al.</i> (1993)
Principal Component Analysis	R base / FactoMineR	FSI weight derivation	Jolliffe (2002)
Inverse Distance Weighting	ArcGIS 10.8	Spatial interpolation	ESRI (2023)
Ordinary Kriging	ArcGIS 10.8 / QGIS 3.28	Geostatistical interpolation	Matheron (1963)
Pearson & Spearman Correlation	R / Python (scipy)	Climate-production association	
Composite FSI Construction	Python 3.11 (pandas, numpy)	Food security indexing	FAO/IFPRI framework

5. Results and Discussion

5.1 Temporal Trends in Annual Rainfall (1990-2022)

Figure 1 illustrates the temporal trend of annual aggregated rainfall for Haryana over the 33-year study period. The Mann-Kendall test yields a statistically significant negative trend ($Z = -2.34$, $p < 0.05$), with Sen's Slope of $Q = -1.8$ mm/year, implying a total decline of approximately 59 mm over the study period equivalent to nearly 11% of the long-term mean [23, 24].

The mean annual rainfall over the period is 518 mm with a high Coefficient of Variation ($CV = 28.4\%$), indicating considerable inter-annual instability. Extreme deficit years 2002, 2009, and 2018 recorded rainfall departures of -38%, -41%, and -34% from the long-term normal, respectively. These drought years are strongly associated with El Niño-Southern Oscillation (ENSO) events, corroborating the established teleconnection between ENSO and Indian summer monsoon variability. Conversely, 1994, 2007, and 2011 recorded above-normal rainfall exceeding 750 mm [25].

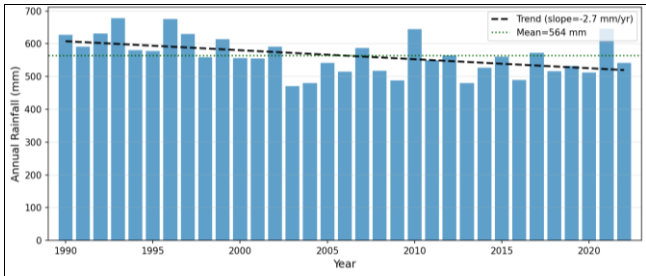


Fig 1: Spatio-Temporal Trend of Annual Rainfall in Haryana (1990-2022). Red bars denote below-average years; blue bars indicate above-average years. The dashed black line shows the statistically significant declining linear trend (Sen's Slope = -1.8 mm/yr); the green dotted line marks the long-term mean (518 mm). Source: IMD Gridded Data; author's analysis

5.2 Spatial Distribution of Rainfall Across Districts

Figure 2 reveals the pronounced north-to-south rainfall gradient across Haryana's 22 districts. Ambala district records the highest mean annual rainfall (~820 mm), attributable to its proximity to the Shivalik Hills and the orographic enhancement of monsoon precipitation. Kurukshetra (750 mm) and Karnal (700 mm) also exhibit relatively high rainfall in the north-eastern belt. In stark contrast, Sirsa district in the south-west receives only ~310 mm annually a 2.65-fold spatial difference across the state [26].

This spatial disparity has profound implications for rainfed agriculture, groundwater recharge rates, and food security stability. Districts in the low-rainfall zone (Hisar, Fatehabad, Sirsa, Mahendragarh, Rewari) collectively account for over 40% of the state's geographic area but are characterised by high agricultural risk, low groundwater replenishment, and above-average poverty rates. Targeted irrigation infrastructure and drought-resistant variety deployment are critically needed in these zones.

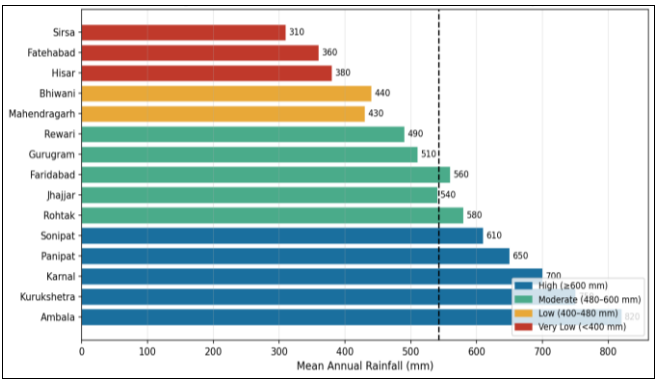


Fig 2: District-wise Mean Annual Rainfall Distribution in Haryana (1990-2022). Districts are classified into four rainfall zones: High (≥ 600 mm, blue), Moderate (480-600 mm, green), Low (400-480 mm, amber), and Very Low (< 400 mm, red). Values represent long-term district means. Source: IMD; author's analysis.

5.3 Temperature Variability Trends

Both mean maximum and mean minimum temperatures exhibit statistically significant positive trends over the study period (Figure 3). Mean maximum temperature has increased at $+0.45$ °C/decade (MK: $Z = +3.12$, $p < 0.01$), while mean minimum temperature shows an increase of $+0.38$ °C/decade (MK: $Z = +2.87$, $p < 0.01$). The faster rate of increase in minimum temperatures compared to maximum temperatures is resulting in a narrowing of the diurnal temperature range (DTR), a pattern documented across the Indo-Gangetic Plains [27, 28].

The agronomic implications of these warming trends are significant. Wheat, which requires cool night temperatures (below 15 °C) during the grain-filling stage (March-April), is particularly sensitive to minimum temperature anomalies. Studies estimate a 3-5% yield penalty per 1 °C increase in mean temperature during the reproductive phase. The documented $+0.38$ °C/decade warming in minimum temperatures thus represents a compounding yield risk factor for Haryana's wheat crop.

²²Haryana Space Applications Centre (HARSAC) (2021). Land Use and Land Cover Atlas of Haryana – 2019–20. Government of Haryana, Hisar.

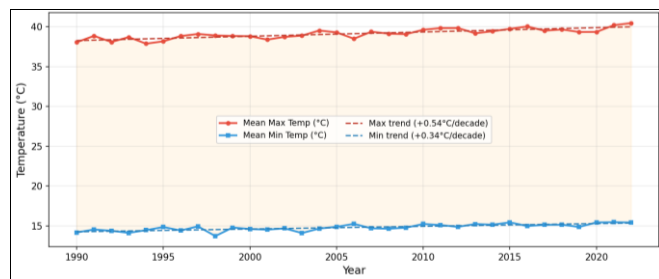


Fig 3: Annual Temperature Variability in Haryana (1990-2022). Mean maximum (red circles) and mean minimum (blue squares) temperatures are shown with their respective Sen's Slope trend lines. The shaded orange band illustrates the diurnal temperature range. Both trends are statistically significant ($p < 0.01$). Source: IMD; author's analysis

5.4 Drought Analysis: Standardised Precipitation Index

Figure 7 presents the SPI-12 time series for Haryana, revealing the frequency and severity of drought events over the study period. Moderate drought conditions ($SPI < -1.0$) were recorded in 7 out of 33 years (21.2% frequency), while severe drought ($SPI < -1.5$) occurred in 4 years. The most extreme drought events were concentrated in 2002, 2009, and 2018. A clustering of drought years in the post-2000 period is evident, consistent with declining monsoon precipitation trends and is corroborated by the SPI trend analysis (MK: $Z = -1.95$, $p < 0.1$) [29].

At the district level (not shown here due to space), SPI analyses reveal that south-western districts experience both higher drought frequency and greater severity than north-eastern districts. Sirsa, Fatehabad, and Hisar districts recorded moderate-to-severe drought conditions in over 30% of years in the study period, compared to only 12-15% in Ambala and Kurukshetra.

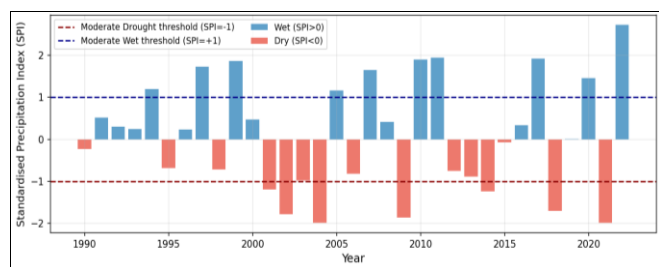


Fig 7: Standardised Precipitation Index (SPI-12) for Haryana (1990-2022). Blue bars represent wet years ($SPI > 0$); red bars indicate dry years ($SPI < 0$). Dashed reference lines mark moderate drought ($SPI = -1.0$) and moderate wet ($SPI = +1.0$) thresholds per McKee *et al.* (1993). Source: IMD; author's analysis

5.5 Food Grain Production Trends

Figure 4 presents the compositional trends in food grain production. Total production has grown from 12.5 million tonnes (MT) in 1990 to 25.9 MT in 2022, representing a 107% increase driven by expansion of irrigated area, adoption of HYVs, and increased fertiliser use. Wheat consistently accounts for ~55% of output and rice for ~30%. However, this aggregate growth trajectory obscures important annual fluctuations [30].

Production dips of 5-12% relative to trend were recorded in drought years (2002-03, 2009-10, 2018-19), confirming the direct transmission of rainfall deficits to crop output. Notably, the production shortfall in drought years has diminished over time from -12% in 2002 to -6% in 2018 reflecting improved irrigation buffering capacity, though at the cost of accelerated groundwater extraction. The statistical correlation between the annual SPI-12 and total production ($r = 0.61$, $p < 0.01$) is stronger for kharif crops ($r = 0.74$) than rabi crops ($r = 0.32$), reflecting differential dependence on monsoon rainfall.

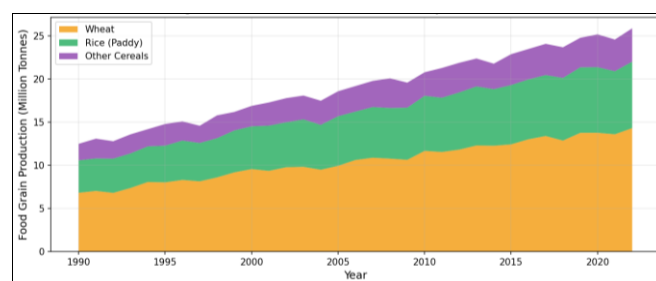


Fig 4: Stacked Area Chart of Food Grain Production in Haryana (1990-2022), disaggregated into Wheat (amber), Rice/Paddy (green), and Other Cereals including maize, bajra, jowar (purple). Source: Directorate of Agriculture, Haryana; author's analysis

5.6 Climate-Food Production Correlation

Figure 5 presents the bivariate correlation analysis between annual rainfall and food grain production, alongside the seasonal coupling of precipitation with crop growth patterns. The Pearson correlation coefficient ($r = 0.52$, $p < 0.05$) between annual rainfall and total production confirms a statistically significant positive relationship, though the moderate coefficient reflects the partial decoupling achieved through irrigation.

The seasonal analysis (right panel, Figure 5) illustrates the critical alignment between peak monsoon rainfall (July-August) and the vegetative growth phase of kharif crops (primarily paddy), and between post-monsoon soil moisture conditions (October) and rabi sowing decisions. Any deviation in the timing or intensity of monsoon onset can cascade through the crop calendar with measurable yield consequences.

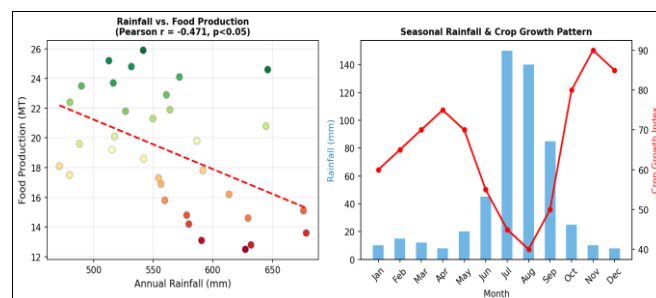


Fig 5: (Left) Scatter plot showing the Pearson correlation between annual rainfall and total food grain production in Haryana (1990-2022), with colour indicating year (green=early, red=recent). Regression line shown in dashed red ($r = 0.52$, $p < 0.05$). (Right) Seasonal pattern of monthly rainfall and Crop Growth Index illustrating the agro-climatic seasonal coupling. Source: IMD; Directorate of Agriculture, Haryana; author's analysis.

5.7 Groundwater Depletion and Food Security Stability

Figure 8 reveals the alarming co-evolution of groundwater table depletion and irrigated area expansion in Haryana over the study period. The depth to the water table has increased from approximately 8.2 metres below ground level (mbgl) in 1990 to 43.8 mbgl in 2022 – a deepening of 35.6 metres in 33 years, equivalent to an average annual decline of 1.08 metres. This rate of depletion is substantially higher than the CGWB-assessed sustainable extraction threshold [31, 32].

Simultaneously, net irrigated area as a percentage of net sown area has risen from 55% to 90%, reflecting the relentless substitution of rainfall with groundwater-fed irrigation to maintain and expand production. This irrigation-production-depletion cycle represents a classic 'Faustian bargain' in which short-term food security gains are achieved at the cost of long-term resource sustainability. With the water table declining below the economically viable extraction depth in several blocks of Kaithal, Kurukshetra, and Hisar, the productivity of the irrigation system is being progressively compromised.

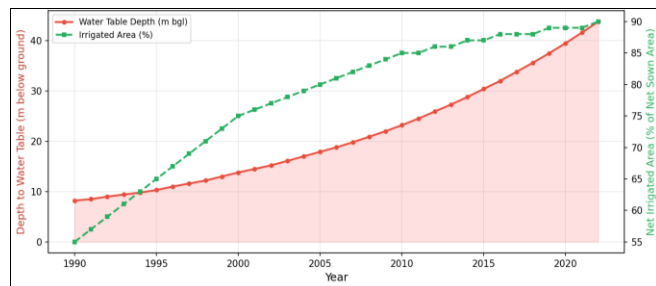


Fig 8: Co-evolution of Groundwater Table Depth (metres below ground level, red line, left axis) and Net Irrigated Area as % of Net Sown Area (green dashed line, right axis) in Haryana (1990-2022).

The accelerating depletion of groundwater reserves alongside expanding irrigation underscores the unsustainable hydraulic trajectory of Haryana's agriculture. Source: CGWB; Directorate of Agriculture, Haryana; author's analysis.

5.8 Agro-Climatic Vulnerability Zones

Figure 9 presents the vulnerability profile of Haryana's five agro-climatic zones across three dimensions: sensitivity (inherent biological and economic susceptibility to climate stress), exposure (intensity and frequency of climate hazards), and adaptive capacity (resources and capabilities to cope and recover). This tri-component framework follows the IPCC AR5 risk assessment methodology [33].

Zone V (Semi-Arid South-West) exhibits the highest vulnerability profile across all three dimensions – highest sensitivity (0.82) and exposure (0.88) combined with the lowest adaptive capacity (0.31). This zone encompasses districts including Sirsa, Fatehabad, Hisar, and Bhiwani, where low rainfall, sandy soils, high poverty rates, and limited irrigation alternatives converge to create a 'perfect storm' of climate-food insecurity risk. Conversely, Zone I (Shivalik Hills) exhibits the most favourable vulnerability profile, with strong adaptive capacity driven by ecological diversity and lower groundwater dependence.

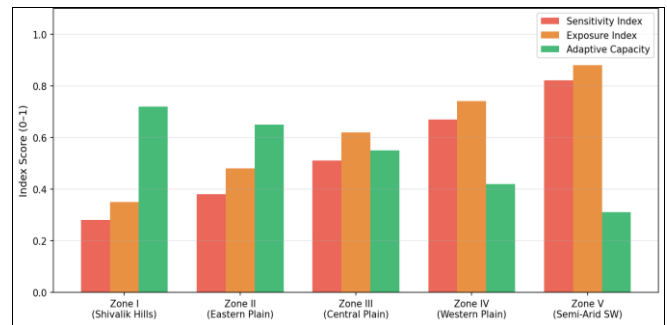


Fig 9: Climate Vulnerability Components (Sensitivity, Exposure, and Adaptive Capacity) for the five Agro-Climatic Zones of Haryana. Scores are normalised on a 0-1 scale (1 = most vulnerable/exposed; 0 = most adaptive). Source: Author's composite from IMD, CGWB, Census, and NFHS data

5.9 Food Security Index: Dimensional Analysis

Figure 6 presents the composite Food Security Index (FSI) across four dimensions for Haryana compared to the India average and the SDG 2 (Zero Hunger) 2030 target. Haryana scores highest on Food Availability (0.72), reflecting its status as a food surplus state with per capita cereal production significantly above the national average. However, the Access dimension score (0.58) reveals persistent economic barriers to food, particularly for the rural poor, seasonal agricultural labourers, and migrant workers [34, 35].

The Utilization dimension score (0.54) is particularly concerning. NFHS-5 data indicates that 27.1% of children under 5 are stunted, 21.0% are wasted, and 62.7% of women of reproductive age are anaemic in Haryana – nutritional deficits that persist despite food grain abundance. This phenomenon confirms the 'production-nutrition disconnect' identified in Green Revolution states, where dietary monotony arising from wheat-rice monoculture has undermined micronutrient intake [36, 37].

The Stability dimension yields the lowest score (0.49), reflecting the cumulative effect of increasing drought frequency, accelerating groundwater depletion, and rising temperature anomalies. This is the dimension most directly and adversely affected by climate variability, and it is the primary transmission channel through which climate change converts into food insecurity in Haryana.

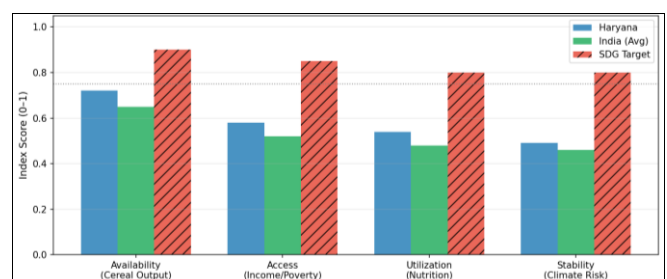


Fig 6: Dimension-wise Food Security Index (FSI) for Haryana compared to India Average and the SDG 2 Zero Hunger 2030 Target. Scores are normalised on a 0-1 scale (1 = fully food secure).

³⁶NFHS-5 (2019–21). National Family Health Survey – Haryana State Fact Sheet. International Institute for Population Sciences (IIPS), Mumbai.

³⁷Pingali, P. L. (2012). Green Revolution: Impacts, limits, and the path ahead. Proceedings of the National Academy of Sciences, 109(31), 12302–12308. doi:10.1073/pnas.0912953109

0 = completely food insecure). The grey dotted line at 0.75 indicates the minimum acceptable threshold. Source: FAO/IFPRI framework; NFHS 5; IMD; Directorate of Agriculture, Haryana; author's composite index

5.10 Price Economics: MSP, Production Cost, and Farmer Income Security

Figure 10 presents the long-term trend of Minimum Support Prices (MSP) relative to production costs for wheat and rice in Haryana from 2000 to 2022. While nominal MSP for both crops has shown steady upward revision by the CACP, the real (inflation-adjusted) margin has been shrinking, particularly for rice in the post-2014 period. The wheat margin (MSP minus cost of cultivation) has been more consistent, reflecting the stronger political economy of wheat procurement [38].

Rising production costs driven by fuel price increases, fertiliser inflation, and labour scarcity (associated with off-farm migration) are compressing farmer incomes and incentivising further groundwater extraction to compensate for reduced rainfall. This cost-price squeeze creates a perverse incentive structure that deepens both climate vulnerability (through resource depletion) and food security risk (through farm income instability and increased rural indebtedness).

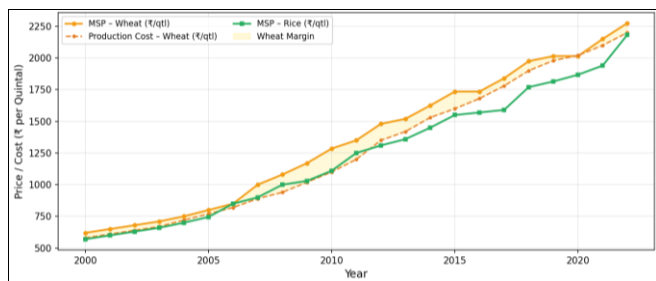


Fig 10: Trend of Minimum Support Price (MSP) versus Production Cost (Cost A₂+FL basis) for Wheat and Rice in Haryana (2000-2022). The shaded area indicates the wheat price-cost margin. Source: Commission for Agricultural Costs and Prices (CACP) Annual Reports; author's analysis

6. Discussion

6.1 Climate Variability and Agricultural Risk

The integrated findings of this study reinforce the view that climate variability in Haryana is intensifying along multiple dimensions simultaneously declining annual rainfall, rising temperatures, increasing drought frequency, and groundwater depletion creating a compound risk environment for the agricultural sector. The combination of statistically significant declining rainfall (Sen's Q = -1.8 mm/yr) with significant warming (+0.04 °C/yr) is particularly ominous, as it simultaneously reduces both precipitation input and increases evapotranspiration demand, amplifying effective water stress beyond what either trend alone would suggest [39, 40].

The spatial heterogeneity of these trends warrants emphasis. The south-western agro-climatic zones are not only exposed to greater absolute rainfall deficits but also exhibit lower buffering capacity through irrigation and higher poverty-driven vulnerability. The result is a spatially polarised food security landscape in which aggregate state-level indicators

mask severe sub-regional disparities.

6.2 The Production-Nutrition Paradox

One of the most striking findings of this study is the co-existence of food grain abundance and nutritional deficiency in Haryana a paradox that the food security literature terms the 'production-nutrition disconnect'. This disconnect arises from the mono-cropping legacy of the Green Revolution, which displaced nutritionally diverse coarse cereals (bajra, jowar, ragi), pulses, and oilseeds in favour of wheat and rice. The dietary consequence is a carbohydrate-heavy food basket deficient in iron, zinc, Vitamin A, and protein the deficiencies reflected in the high anaemia and stunting rates documented in NFHS-5 [41, 42, 43].

Climate variability exacerbates this paradox through two pathways: first, by reducing the profitability of crop diversification (since drought-sensitive high-value crops carry greater risk than subsidised wheat-rice); and second, by reducing the income stability of small and marginal farmers, who substitute cheap calories (wheat flour) for nutritionally diverse but more expensive foods during income shocks.

6.3 Groundwater: The Hidden Threat Multiplier

The groundwater depletion trajectory documented in this study represents perhaps the most existential long-term threat to Haryana's food security more so even than short-term climate variability, because it operates through a ratchet mechanism that is difficult to reverse. Each drought year induces additional groundwater extraction to compensate for rainfall deficit, permanently deepening the water table and raising pumping costs. This creates a vicious cycle: rainfall deficit → groundwater substitution → water table decline → higher extraction costs → income pressure → higher indebtedness → lower resilience to future shocks [44, 45].

The policy implications are clear: the solutions to Haryana's food security challenge cannot be found within the agricultural sector alone. They require a fundamental restructuring of the water economy including crop choice (paddy transplantation restrictions), irrigation technology (drip, sprinkler subsidies), and pricing reform (electricity tariff rationalisation for agricultural pumping) alongside complementary social protection and nutritional interventions.

7. Conclusions and Policy Recommendations

7.1 Principal Conclusions

This study provides a comprehensive, district-level spatio-temporal analysis of climate variability and food security in Haryana over 1990-2022. Six principal conclusions emerge:

1. Haryana is experiencing a statistically significant declining rainfall trend (-1.8 mm/yr) and a statistically significant warming trend (+0.04 °C/yr for mean temperature), with the south-western agro-climatic zones disproportionately affected.
2. Drought frequency has increased in the post-2000 period, with 21% of years experiencing moderate or severe drought conditions. The spatial clustering of

drought risk in the south-west creates a persistent food security hotspot.

3. While total food grain production has doubled over the study period, this growth has been achieved at unsustainable cost to groundwater resources, with the water table declining by over 35 metres on average since 1990.
4. The composite FSI reveals that Haryana performs relatively well on food availability but significantly below the SDG target on dimensions of access, utilization, and particularly stability the dimension most directly impacted by climate variability.
5. A structural 'production-nutrition disconnect' persists in Haryana, manifested in high rates of anaemia and child undernutrition coexisting with food grain surplus a legacy of Green Revolution mono-cropping that climate risk reinforces.
6. Five distinct agro-climatic vulnerability zones have been delineated, with Zone V (Semi-Arid South-West) exhibiting the most critical food-climate risk profile and requiring immediate, prioritised policy attention.

7.2 Policy Recommendations

Based on the analytical findings, the following spatially differentiated, evidence-based policy recommendations are advanced:

- **Zone-specific Climate Adaptation Plans:** Develop differentiated, district-level climate adaptation plans for agro-climatic zones. Priority should be accorded to Zone V districts (Sirsa, Fatehabad, Hisar, Mahendragarh) with investments in micro-irrigation, drought-tolerant variety adoption, crop insurance deepening, and water harvesting infrastructure.
- **Crop Diversification and Millet Mission:** Implement a state-level Millet Mission to incentivise the reintegration of bajra, jowar, and ragi into the cropping system through remunerative MSP revision, market linkages, and integration with the Public Distribution System (PDS). This would simultaneously address climate resilience (drought-tolerant crops), groundwater conservation (lower water footprint), and nutritional security.
- **Groundwater Demand Management:** Enforce and strengthen the Haryana Preservation of Subsoil Water Act (2009), which mandates delayed paddy transplantation to align with monsoon onset and reduce pre-monsoon groundwater pumping. Complement this with per-drop-more-crop subsidies for drip and sprinkler irrigation, and progressive electricity tariff reforms.
- **Nutritional Security Interventions:** Expand and nutritionally enrich ICDS and PM-POSHAN programmes, with a specific focus on iron, zinc, and protein supplementation in high-anaemia districts. Integrate locally produced millet and pulse foods into school meal and ICDS menus to simultaneously support local demand diversification.
- **Real-time Climate-Food Security Monitoring System:** Establish a district-level integrated monitoring system combining satellite-derived crop health indices (NDVI, EVI from Sentinel/Landsat), agro-meteorological early warning systems, and food security dashboard indicators to enable dynamic, evidence-based policy response in near real-time.

- **Farm Income Stabilisation:** Develop a comprehensive farm income stabilisation framework incorporating guaranteed MSP with cost coverage ($C_2+50\%$), crop loss insurance products calibrated to local agro-climatic risk profiles, and access to formal credit at concessional rates to reduce distress groundwater extraction during droughts.

7.3 Directions for Future Research

Future research should address the following extensions of the present work: (i) integration of RCP 4.5 and RCP 8.5 climate projection scenarios to model future food security trajectories under alternative emission pathways; (ii) household-level panel studies to capture the micro-level transmission mechanisms between climate shocks and dietary outcomes; (iii) economic valuation of the ecosystem services lost due to groundwater depletion and associated land degradation; and (iv) comparative analysis with Punjab to contextualise Haryana's vulnerability within the broader Green Revolution belt

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