



Climate Variability, Groundwater Depletion, and Their Effects on Cropping Patterns in Jhunjhunu District: A Geospatial Study

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ABSTRACT

Climate variability and groundwater depletion are increasingly restructuring agricultural systems in semi-arid regions of India. Jhunjhunu district, located in the north-eastern part of Rajasthan, presents a significant case where rainfall uncertainty, rising temperature, recurrent drought conditions, and declining groundwater levels are simultaneously influencing cultivation decisions. The district's agrarian economy has long depended on fragile monsoon behavior and extensive dependence on tube-well irrigation, making cropping choices highly sensitive to climatic and hydrological stress. In such a context, a geospatial approach becomes especially useful because it helps connect environmental trends with spatial changes in land use, irrigation dependence, and crop distribution. This article examines how climate variability and falling groundwater resources are reshaping cropping patterns in Jhunjhunu district and how these changes affect the sustainability of local agriculture.

The study adopts an analytical and descriptive approach based on secondary data, district-level agricultural records, groundwater reports, and geospatial interpretation of land use and vegetation change. The article argues that shifts in rainfall timing, increasing dry spells, heat stress, and groundwater decline are jointly encouraging movement away from water-intensive or risk-prone cultivation toward more defensive and adaptive cropping strategies. Farmers are increasingly compelled to alter sowing decisions, reduce irrigated acreage, diversify toward hardy crops, or leave fields partially uncultivated in unfavorable years. The geospatial perspective shows that the crisis is not uniform across the district; rather, it varies according to water access, agro-ecological conditions, and irrigation infrastructure. The article concludes that cropping pattern change in Jhunjhunu is not merely an agronomic adjustment but a spatial expression of climate stress and groundwater scarcity, requiring integrated water management, crop planning, and region-specific adaptation strategies.

Keywords: Climate variability; groundwater depletion; cropping pattern; agricultural sustainability; Jhunjhunu district; geospatial study; irrigation stress

1. INTRODUCTION

Agriculture in semi-arid India has always been shaped by uncertainty, but the nature of that uncertainty has become sharper and more complex under contemporary climate stress. Rainfall is increasingly erratic, temperatures are rising, and groundwater reserves are under pressure from excessive extraction and inadequate recharge. In districts like Jhunjhunu, where rural livelihoods remain closely linked with farming, these environmental pressures have begun to alter the basic structure of crop planning. Farmers are no longer responding only to soil suitability, market demand, or traditional agrarian calendars; they are now compelled to respond to unstable rainfall, falling water tables, and increased production risk. In this changing context, the study of cropping patterns becomes a valuable window through which broader ecological and economic transformations can be understood.

Jhunjhunu district is particularly suitable for such an inquiry because it represents a transitional agricultural landscape within Rajasthan where monsoon dependence coexists with groundwater-based irrigation. In many parts of the district, tube wells and bore wells have enabled agricultural intensification over several decades. However, this model has become increasingly fragile as groundwater depth has increased and climate variability has affected recharge conditions. Cropping patterns that were once viable under relatively stable hydrological conditions are now becoming difficult to sustain. Thus, examining how climate variability and groundwater depletion influence crop choices is essential not only for understanding agricultural change but also for formulating regionally grounded policy responses.

This article approaches the issue through a geospatial lens. Geospatial analysis offers the ability to observe environmental stress across space rather than treating the district as a single homogeneous unit. It helps identify



areas where cropping intensity has declined, where irrigated land has become unstable, and where vulnerability is concentrated. The purpose of this study is therefore to explain the relationship between climate variability, groundwater depletion, and cropping pattern transformation in Jhunjhunu, while also emphasizing the policy relevance of spatially informed agricultural planning.

REVIEW OF LITERATURE

The literature on climate-agriculture interactions in dryland India shows that rainfall variability, temperature rise, and groundwater decline are among the most significant drivers of agrarian instability. A large body of scholarship has demonstrated that semi-arid districts are especially vulnerable because they rely on a narrow ecological margin in which small changes in rainfall timing or irrigation availability can produce substantial effects on productivity and crop choice. Studies on Rajasthan have repeatedly noted that climate stress is not expressed only through crop failure; it also appears through delayed sowing, reduced crop intensity, increased fallowing, and a shift toward low-risk cultivation. This makes cropping pattern analysis an important indicator of agricultural adaptation and distress.

Research on groundwater depletion has likewise emphasized its structural role in shaping agricultural decisions. In many regions of India, groundwater expansion initially supported crop intensification and reduced dependence on monsoon uncertainty. Yet over time, declining aquifers have led to rising energy costs, uneven irrigation access, and declining viability of water-demanding crops. Scholars working on western and north-western India have shown that farmers often respond to falling water tables by reducing irrigated area, changing from commercial to subsistence-oriented crops, or switching from multi-cropping to a more conservative seasonal regime. These adjustments are especially important in districts where water availability determines not only yields but also the feasibility of entire cropping calendars.

The literature on geospatial analysis provides an additional methodological foundation for this article. Remote sensing and GIS have increasingly been used to examine land use and land cover change, vegetation response, moisture stress, cropping intensity, and spatial variations in agricultural risk. Satellite-based interpretation allows researchers to move beyond purely tabular statistics and to identify local patterns that district averages often hide. In regions facing groundwater and climate stress, geospatial approaches help correlate vegetation decline, changes in irrigated land, and land-use transitions with environmental variables. However, there remains a need for more district-level studies that explicitly link climate variability and groundwater decline to cropping pattern transformation through a geospatial perspective. The present article attempts to contribute to that gap in the context of Jhunjhunu district.

2. OBJECTIVES OF THE STUDY

The study has been designed with a set of interrelated objectives. First, it seeks to examine the nature of climate variability and groundwater depletion in Jhunjhunu district and to understand how these two processes are reshaping the agricultural environment. Second, it aims to analyze the changing cropping patterns of the district in relation to rainfall uncertainty, heat stress, and irrigation stress. Third, it attempts to explain the spatial unevenness of agricultural change by drawing on geospatial interpretation. Fourth, it aims to compare the relative influence of climate variability and groundwater decline on cropping decisions. Finally, the study seeks to suggest region-specific strategies for improving agricultural sustainability under emerging environmental stress.

3. RESEARCH METHODOLOGY

The present article is analytical, descriptive, and conceptual in design, while also relying on a geospatial mode of interpretation. It is based primarily on secondary sources such as district statistical records, agricultural reports, groundwater assessments, remote sensing-based interpretations, and relevant academic literature on climate change, irrigation, land use, and agrarian adaptation in semi-arid regions. The study does not depend on primary field surveys, but it is framed in such a way that district-level empirical observations from published sources can be synthesized with spatial reasoning.

The geospatial element of the article is interpretive rather than purely technical. The study draws conceptually on the use of GIS, land-use analysis, vegetation indices, rainfall mapping, and spatial comparison of hydrological stress zones. Such techniques are useful in identifying areas of intense water stress, changes in cultivable land, shifts in cropping intensity, and vulnerability clustering. By relating environmental indicators to agricultural trends, the article builds a spatially grounded explanation of cropping pattern change. The unit of analysis is Jhunjhunu district as a whole, while recognizing intra-district variation across blocks and farming zones.

The methodology also uses comparative reasoning. Climate variability and groundwater depletion are treated as linked but analytically separable forces. This makes it possible to examine whether crop change is being driven more by rainfall instability, more by irrigation collapse, or by the interaction of both. The analytical framework therefore integrates three dimensions: climatic stress, groundwater stress, and agrarian response. Through this



framework, the article interprets cropping pattern change as a cumulative outcome of environmental pressure rather than as a simple one-factor adjustment.

4. STUDY AREA PROFILE: JHUNJHUNU DISTRICT

Jhunjhunu district lies in the north-eastern part of Rajasthan and forms an important part of the Shekhawati region. The district exhibits semi-arid conditions characterized by low and variable rainfall, high summer temperatures, significant evapotranspiration, and ecological stress associated with limited water availability. Agriculture remains a major source of livelihood, although the nature of farming differs across blocks depending on landholding patterns, irrigation access, and local agro-climatic conditions. The district supports both rainfed and irrigated agriculture, but groundwater has become central to cultivation wherever canal irrigation or surface storage is insufficient.

The district's agriculture has historically depended on monsoon timing and localized irrigation support. Traditional crops in the region include cereals, pulses, oilseeds, fodder crops, and limited commercial cultivation depending on water access. Over time, the spread of tube wells enabled expansion of irrigated farming, but this also increased pressure on underground aquifers. In many villages, the depth of groundwater extraction has risen, the quality of water has become a concern, and the cost of irrigation has increased. These factors have created a condition in which agricultural sustainability is no longer determined only by land productivity but by the availability and reliability of water.

From a geospatial perspective, Jhunjhunu is not environmentally uniform. Variations in topography, soil characteristics, settlement density, and irrigation access produce different patterns of vulnerability. Some areas are more exposed to recurrent moisture stress, while others are more affected by extraction-induced groundwater decline. Thus, the district profile itself indicates the need for spatially disaggregated agricultural planning rather than one uniform adaptation strategy.

Conceptual Understanding of Climate Variability and Groundwater Depletion

Climate variability refers to fluctuations in climatic conditions such as rainfall amount, rainfall distribution, temperature, onset of monsoon, duration of wet spells, and frequency of extreme events. In agrarian regions, climate variability matters not merely because weather changes occur, but because such changes disturb the biological and managerial rhythm of cultivation. A delayed monsoon may postpone sowing, erratic rainfall may reduce germination, and prolonged dry spells may damage crops at critical growth stages. In dryland districts, variability can be more damaging than average deficiency because agricultural planning relies heavily on timing and predictability. For farmers, uncertainty itself becomes a production risk.

Groundwater depletion, on the other hand, refers to the decline in underground water reserves caused by extraction exceeding recharge over a prolonged period. In farming systems dependent on tube-well irrigation, groundwater depletion affects both quantity and accessibility. Even when some water remains, greater depth raises pumping costs and makes irrigation uneven across households. The issue therefore extends beyond hydrology into economics and social differentiation. Farmers with better capital or access to deep bore technology may continue irrigating for some time, while small and marginal cultivators may be forced to reduce crop area or shift toward less water-intensive alternatives.

The relationship between climate variability and groundwater depletion is mutually reinforcing. Weak or erratic rainfall reduces recharge and increases dependence on pumping. In turn, greater pumping accelerates groundwater decline and makes agriculture even more vulnerable in subsequent dry years. This interaction is particularly visible in semi-arid districts such as Jhunjhunu, where climate stress and irrigation dependence are closely entangled. Thus, cropping pattern change must be understood as an outcome of both atmospheric uncertainty and hydrological exhaustion.

Cropping Patterns in Jhunjhunu District

Cropping pattern refers to the proportion of area allocated to different crops within a given agricultural system. It reflects ecological suitability, irrigation availability, market conditions, household needs, and risk perception. In Jhunjhunu, cropping patterns have long been shaped by the constraints of a semi-arid environment. Traditional cultivation has favored crops capable of surviving limited water conditions, while irrigated areas have supported more diversified or commercially attractive options. Seasonal distinctions between kharif and rabi cultivation remain crucial, and the viability of each season depends on a changing balance between rainfall and irrigation.

Over time, the district has witnessed shifts in acreage under cereals, pulses, oilseeds, fodder crops, and cash-oriented cultivation. These changes cannot be explained solely by price incentives. In many cases, changes in crop composition have followed patterns of water availability and climatic stress. Farmers often prefer crops with lower water demand, shorter duration, or greater resilience to rainfall irregularity. In years of severe stress, farmers may reduce the cultivated area itself, rely more heavily on fodder or subsistence crops, or avoid risky investments in high-input cultivation. Thus, cropping pattern is best interpreted as an adaptive map of agrarian decision-making. A geospatial reading of cropping patterns also highlights that change is uneven. Areas with relatively better groundwater access may continue diversified cultivation for longer periods, while areas facing severe aquifer



decline may move toward defensive strategies earlier. Therefore, the district's cropping pattern is not a static agricultural profile but a dynamic response shaped by spatial differences in water security and exposure to climate variability.

Impact of Climate Variability on Cropping Patterns

Climate variability affects cropping patterns in Jhunjhunu through multiple channels. The first is rainfall uncertainty. When monsoon onset becomes delayed or irregular, farmers may postpone sowing or abandon certain crops altogether. Crops that depend on timely rainfall for germination become increasingly risky, and this often leads to a move toward drought-tolerant or shorter-duration varieties. The second channel is temperature stress. Higher temperatures raise evapotranspiration, shorten crop growth stages, and increase the vulnerability of standing crops during critical reproductive periods. Together, these factors can reduce the attractiveness of crops that once performed reasonably well under earlier climatic conditions.

Another important effect of climate variability is the disruption of agricultural planning. Farmers make decisions before the season begins, often with incomplete information. When rainfall becomes erratic, the reliability of traditional knowledge declines and crop planning becomes more uncertain. This uncertainty encourages conservative behavior. Farmers may reduce investment in fertilizer, choose crops with lower expected returns but lower risk, or split land among multiple crops to hedge against climatic failure. Such strategies alter the district's aggregate cropping pattern by reducing specialization and increasing risk-avoidance.

Climate variability also contributes to instability in cropping intensity. In years of prolonged drought or poor rainfall distribution, some fields may remain fallow or may support only a single crop rather than multiple seasonal cycles. Geospatially, these changes can be detected in variations in vegetation cover, seasonal cultivation extent, and moisture-linked land-use behavior. Thus, the effect of climate variability is not confined to yield loss; it changes the very structure, timing, and composition of cultivation across space.

Impact of Groundwater Depletion on Cropping Patterns

Groundwater depletion alters cropping patterns in a more structural and long-term manner. Where agriculture has become dependent on tube-well irrigation, declining groundwater levels reduce the certainty that irrigation can be sustained across the season. This affects crop choice directly. Farmers become less willing to cultivate crops that require repeated irrigation or high water assurance. They may shift toward crops with lower water demand, less intensive management needs, or lower market risk. In areas where groundwater levels have fallen sharply, even rabi cultivation can become difficult, leading to reductions in seasonal diversification.

The economic effects of groundwater depletion are equally significant. Deeper pumping means higher energy use, more frequent well failure, increased maintenance costs, and inequality in irrigation access. Larger farmers may be able to continue groundwater extraction by investing in deeper bore wells or improved pumps, but small cultivators often face reduced access. This creates a differentiated cropping landscape where resource-rich farmers maintain some degree of crop flexibility while poorer farmers become confined to low-input or rainfed options. As a result, groundwater depletion not only changes crop patterns but also reshapes agrarian inequality.

From a spatial perspective, groundwater depletion produces visible agricultural signatures. Areas of severe decline often show reduced irrigated acreage, lower cropping intensity, and stronger dependence on hardy crops or fodder cultivation. In some locations, repeated groundwater stress may even contribute to gradual disinvestment from farming. Thus, groundwater decline is not just a water problem; it is a force that reconfigures agricultural geography in Jhunjhunu.

Role of Geospatial Techniques in Analyzing Agricultural Change

Geospatial techniques offer a powerful framework for understanding environmental stress in agricultural regions because they reveal patterns that conventional descriptive statistics cannot capture. In the context of Jhunjhunu, remote sensing and GIS can be used to map land-use change, spatial variation in vegetation vigor, irrigated versus non-irrigated land, and zones of recurrent agricultural stress. Such methods make it possible to examine whether changes in cropping intensity or cultivated area correspond with areas of groundwater decline or climatic exposure. In effect, they transform scattered environmental and agrarian indicators into a spatial narrative.

Geospatial analysis is especially useful in semi-arid regions because environmental stress is rarely uniform. Two blocks within the same district may experience very different groundwater conditions or cropping responses. Spatial mapping can identify hotspots of vulnerability, areas of adaptation, and local contrasts in land-use response. It can also help compare temporal changes, such as shifts from one crop season to another, decline in green cover, or contraction of irrigated zones. This is important for policy because administrative averages often mask clusters of acute distress.

The geospatial approach is therefore not merely technical decoration; it has interpretive value. It allows agricultural change to be seen as a spatial process shaped by water access, environmental risk, and resource inequality. In a district such as Jhunjhunu, where climate and groundwater interact unevenly, geospatial techniques support more precise diagnosis and more localized adaptation planning.



Comparative Analysis of Climate Variability and Groundwater Depletion

Climate variability and groundwater depletion do not operate in isolation, yet their effects on cropping patterns differ in character. Climate variability tends to produce seasonal uncertainty. It influences sowing decisions, crop risk, and yearly fluctuations in cultivated area. Its effects are immediate and often visible within a single agricultural season. Groundwater depletion, by contrast, produces cumulative structural change. It affects the long-term viability of irrigation-dependent agriculture and reshapes the economic foundation of farming over time. While climate variability may trigger short-term adaptation, groundwater decline pushes agriculture toward deeper reorganization.

In Jhunjhunu, the two forces are best understood as interacting layers of risk. When rainfall is poor, dependence on groundwater increases. When groundwater has already declined, the capacity to buffer rainfall failure becomes weak. Under such conditions, farmers face a compounded crisis in which both atmospheric and subsurface water insecurity constrain crop choice. This explains why cropping pattern shifts are often more severe in areas where both rainfall stress and groundwater depletion are simultaneously present. In such areas, farmers are not simply adapting to bad weather; they are adapting to a shrinking water future.

Comparatively, it may be argued that groundwater depletion has the stronger long-term effect because it reduces the irrigation resilience that once allowed agriculture to absorb climatic shocks. However, climate variability remains the more visible seasonal trigger of change. The cropping pattern in Jhunjhunu is therefore shaped by a layered interaction in which climate acts as an immediate disturbance and groundwater decline acts as a structural limitation.

5. CHALLENGES FACED BY FARMERS

Farmers in Jhunjhunu face a combination of ecological and economic challenges that complicate agricultural adaptation. Water scarcity is the most visible problem, but it interacts with rising input costs, uncertain output prices, and weak institutional support. When groundwater declines, irrigation becomes costlier and less reliable. When rainfall becomes erratic, even carefully planned cultivation may fail. This double burden discourages investment and pushes many households toward conservative cropping choices that prioritize survival over profitability.

Another major challenge is information uncertainty. Farmers often lack timely climate advisories, local groundwater data, or practical guidance on crop-water suitability under changing conditions. Adaptation therefore occurs through trial, experience, and informal local knowledge rather than through systematic support. This can produce delayed or suboptimal responses. Furthermore, inequalities in landholding, credit access, irrigation infrastructure, and technology adoption mean that not all farmers can respond to stress in the same way. The burden of adjustment falls more heavily on small and marginal cultivators.

Livelihood insecurity also grows when cropping patterns become unstable. Reduced productivity, crop failure, and shrinking irrigation opportunities may compel households to diversify into wage labor, livestock dependence, or migration. Therefore, the challenge is not merely agricultural. It concerns the wider stability of rural life and the ability of agrarian households to remain resilient under repeated environmental pressure.

6. SUGGESTIONS AND POLICY IMPLICATIONS

The findings of the study suggest the need for integrated and spatially differentiated policy responses. First, groundwater management must become central to agricultural planning in Jhunjhunu. This requires stronger regulation of extraction, promotion of recharge measures, restoration of traditional water bodies, and incentives for water-conserving irrigation practices. Policies should move beyond generic conservation appeals and instead identify high-stress blocks for priority intervention. Geospatial mapping can play an important role in such targeting.

Second, crop planning must be aligned with agro-climatic and hydrological realities. Farmers require practical support in shifting toward crops and varieties that are suitable for semi-arid conditions, lower in water demand, and less vulnerable to heat and rainfall irregularity. Agricultural extension should focus on crop-water budgeting, seasonal advisories, and diversification strategies that reduce risk without undermining livelihood viability. In addition, weather-based crop insurance and localized drought preparedness measures should be strengthened.

Third, policy must recognize that environmental stress is spatially uneven and socially differentiated. Adaptation strategies should support smallholders through credit, irrigation access, decentralized water harvesting, and community-based resource management. Geospatial tools should be integrated into district planning to identify hotspots of agricultural decline, groundwater pressure, and livelihood vulnerability. A district such as Jhunjhunu requires not one broad solution but a portfolio of location-specific interventions that connect water, crops, and rural resilience.



7. CONCLUSION

The article demonstrates that cropping pattern change in Jhunjhunu district is closely linked with the combined pressure of climate variability and groundwater depletion. Rainfall uncertainty, rising temperatures, dry spells, and declining recharge have intensified the vulnerability of agriculture in a region already constrained by semi-arid conditions. At the same time, falling groundwater levels have reduced irrigation reliability and altered the long-term viability of several cropping choices. Farmers are responding through shifts in crop selection, reductions in cropping intensity, and more cautious forms of agricultural management. These changes reflect adaptation, but they also reveal growing ecological stress and agrarian fragility.

A geospatial perspective helps clarify that these transformations are unevenly distributed across the district. Some areas experience severe water stress and visible contraction in cultivation, while others retain limited resilience due to relatively better access to groundwater or irrigation infrastructure. This spatial unevenness is crucial for policy. Broad district-level averages cannot adequately capture the emerging geography of agricultural vulnerability. Sustainable agricultural planning in Jhunjhunu must therefore be grounded in location-specific assessment.

Ultimately, the study suggests that agricultural sustainability in the district depends on restoring the relationship between water availability and crop planning. Climate variability may not be fully controllable, but its impacts can be reduced when groundwater governance, geospatial monitoring, adaptive crop strategies, and farmer support systems work together. The future of cropping patterns in Jhunjhunu will depend on whether policy can shift from reactive crisis management to proactive, water-sensitive, and spatially informed agricultural adaptation.

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