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Declining Water Level in Mahendergarh District, Haryana: A Challenge for Sustainability

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ABSTRACT: Mahendergarh district in southern Haryana faces acute groundwater stress amid semi-arid conditions and heavy dependence on underground sources for agriculture and domestic needs. Long-term monitoring reveals a marked drop in water tables, with the district average depth reaching approximately 50.93 meters below ground level by 2023. Over 81 percent of the area now registers depths exceeding 30 meters, placing large portions in the extremely deep category. Certain blocks, including Ateli, Satnali, and Mahendergarh, have experienced declines surpassing 30 meters between 1991 and 2023, while extraction stages in several blocks consistently exceed 100 percent of annual recharge.119935

Primary drivers include intensive cultivation of water-demanding crops, widespread use of subsidized electricity for tube wells, limited natural recharge due to low and erratic rainfall (typically 300–500 mm annually), and rocky terrain with poor infiltration capacity. These pressures have widened the gap between extraction and replenishment, resulting in falling yields, higher pumping costs, and risks to rural livelihoods. Secondary effects encompass reduced availability for household supply, potential quality deterioration in isolated pockets, and threats to local ecosystem stability.

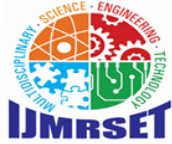
This study synthesizes spatio-temporal trends from official hydrogeological records up to 2024 assessments, evaluates underlying causative factors, and assesses socio-economic and environmental consequences. It proposes integrated remedial measures such as precision irrigation techniques, crop pattern shifts toward less water-intensive varieties, enhanced rainwater harvesting structures, and community-led governance frameworks. Urgent adoption of these strategies is essential to restore balance, safeguard agricultural productivity, and ensure long-term resource viability in this vulnerable district.

KEYWORDS: Groundwater depletion, Mahendergarh district, Haryana, aquifer sustainability, over-extraction, semi-arid hydrology, water management strategies, recharge enhancement.

I. INTRODUCTION

Groundwater constitutes a vital yet finite resource underpinning agricultural productivity, domestic water security, and ecological stability across vast stretches of the planet. In regions characterized by limited surface water and erratic precipitation patterns, aquifers serve as the primary buffer against seasonal variability, supporting livelihoods for billions while sustaining food systems that feed growing populations. However, intensified human interventions, including large-scale irrigation expansion and urban-industrial demands, have accelerated extraction rates far beyond natural replenishment capacities in many basins. This imbalance has manifested in widespread aquifer depletion, land subsidence, and deteriorating water quality, posing existential threats to long-term sustainability. Climate change compounds these pressures by altering rainfall regimes, intensifying evaporation, and increasing the frequency of extreme weather events that disrupt recharge cycles. The resultant crisis transcends mere hydrological concerns, encompassing socioeconomic disruptions, food insecurity, and intergenerational equity dilemmas that demand integrated scientific inquiry and policy innovation.

Within the Indian context, groundwater dependency has escalated dramatically since the advent of the Green Revolution, transforming the country into one of the world's largest users of subterranean resources. The Indo-Gangetic plains and adjacent semi-arid zones, once reliant on canal networks, have shifted toward tube-well irrigation to meet the demands of high-yielding crop varieties. This transition, while boosting yields in the short term, has strained aquifers in



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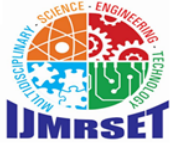
northwestern states where over-extraction now outpaces recharge in extensive areas. Arid and semi-arid tracts, in particular, exhibit pronounced vulnerability due to low permeability formations, sparse vegetation cover, and high evapotranspiration losses. National hydrogeological evaluations consistently highlight northwestern India as a hotspot where extraction stages frequently surpass 100 percent of annual replenishable resources, leading to progressive deepening of water tables and associated infrastructural challenges. Such trends not only threaten agrarian economies but also undermine rural employment, exacerbate migration pressures, and heighten conflicts over diminishing shared resources among competing user groups.

Haryana, positioned in the heart of this northwestern agrarian landscape, exemplifies the tensions inherent in intensive farming systems operating under constrained hydrological regimes. The state's economy remains overwhelmingly tied to agriculture, with irrigated cropping patterns dominating land use and contributing substantially to national grain production. Yet, the absence of perennial rivers across much of its territory has necessitated heavy dependence on groundwater, which accounts for the bulk of irrigation and domestic supplies. Decades of subsidized energy policies and free or low-cost electricity have incentivized unchecked pumping, particularly in areas lacking robust surface water infrastructure. This has resulted in heterogeneous depletion patterns, with southern and western districts displaying accelerated declines compared to northern counterparts blessed with canal commands. The interplay of geological heterogeneity, including alluvial deposits interspersed with harder rock formations, further modulates recharge potential, rendering certain locales inherently more susceptible to stress. Moreover, shifting climatic signals—marked by reduced monsoon reliability and rising temperatures—have diminished the efficacy of natural recharge mechanisms, amplifying the urgency for district-specific interventions that align extraction with replenishment dynamics.

Mahendergarh district, located in southern Haryana along the fringes of the Aravalli hill ranges, epitomizes these regional vulnerabilities while presenting unique hydrogeological and socioeconomic dimensions. Its topography features undulating plains punctuated by rocky outcrops and residual hills, which constrain surface runoff and limit the development of extensive canal systems. Annual precipitation typically hovers between 300 and 500 millimeters, predominantly concentrated in the monsoon months, yet marked by high inter-annual variability that hampers consistent aquifer replenishment. The underlying geology comprises a mix of sedimentary and fractured crystalline formations, where secondary porosity governs groundwater occurrence and movement, often resulting in low storage yields and variable transmissivity. Agriculture forms the cornerstone of the local economy, with kharif and rabi seasons dominated by crops requiring substantial irrigation inputs amid negligible contributions from surface sources. Population growth, coupled with expanding cultivated areas and livestock rearing, has intensified demand, transforming groundwater into the lifeline for thousands of farming households. This reliance has fostered a cycle of deepening dependence, wherein initial yield gains from expanded irrigation have gradually given way to escalating pumping depths and energy expenditures.

The consequences of sustained water table recession in Mahendergarh extend beyond immediate hydrological metrics to encompass multifaceted risks to sustainability. Declining levels elevate operational costs for farmers, erode profit margins in already marginal agrarian settings, and threaten the viability of smallholder operations that predominate the district. Domestic water supplies, often sourced from the same aquifers, face reliability issues, particularly during lean periods, thereby impacting public health and gender equity as women bear disproportionate burdens in water collection. Ecosystem services, including baseflow to seasonal streams and support for local biodiversity, diminish as aquifers deplete, potentially triggering habitat fragmentation and reduced resilience to drought. At a broader scale, unchecked depletion undermines food security contributions from the district while exacerbating regional disparities in resource access. Policy frameworks, though evolving through national missions on water conservation and state-level initiatives, have yet to achieve granular implementation tailored to the district's fractured aquifers and socio-cultural contexts.

This study addresses these interlocking challenges by systematically examining the spatio-temporal evolution of groundwater levels in Mahendergarh, elucidating causative mechanisms rooted in land-use practices, climatic influences, and governance gaps. It further evaluates the cascading impacts on agricultural viability, livelihood security, and environmental integrity, culminating in evidence-based pathways for restorative management. By integrating hydrogeological data with socioeconomic insights, the analysis underscores the imperative for adaptive strategies that reconcile productivity imperatives with ecological limits. Such an approach not only illuminates district-specific dynamics but also offers transferable lessons for analogous semi-arid locales confronting similar sustainability frontiers. Ultimately, reversing depletion trends in Mahendergarh holds profound implications for fostering resilient rural economies, safeguarding water equity, and advancing the broader goals of sustainable development in water-stressed



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regions of India. The ensuing sections delineate the methodological foundations, empirical findings, interpretive analyses, and forward-looking recommendations derived from this investigation, providing a comprehensive framework for informed decision-making and community engagement.

II. REVIEW OF EXISTING STUDIES

Institutional assessments by the Central Ground Water Board have systematically documented the escalation of aquifer stress across Haryana, identifying southern districts including Mahendergarh as hotspots of chronic over-exploitation. Dynamic groundwater resource evaluations reveal that extraction frequently surpasses annual recharge, with several blocks in the district categorized as over-exploited due to intensive tube-well irrigation and limited surface water alternatives. State-level analyses trace the transition from canal-dominated systems to groundwater dependency post-Green Revolution, noting that extraction stages in western and southern zones often exceed 100 percent, leading to progressive deepening of water tables.

Scholarly investigations into regional hydrogeology emphasize the influence of Aravalli fringe topography on recharge limitations. Studies highlight low and erratic rainfall patterns coupled with rocky formations that restrict infiltration, resulting in sustained declines averaging over one meter annually in vulnerable districts since the early 2010s. Block-wise disaggregation shows cumulative drops exceeding 30 meters in certain pockets of Mahendergarh between baseline periods and recent monitoring cycles, with over 80 percent of the area recording depths beyond 30 meters below ground level. Complementary research on irrigation development correlates the proliferation of energized wells with darkened categorization of assessment units, projecting risks to long-term agricultural viability under prevailing crop patterns.

Hydrochemical evaluations across Haryana have further linked over-extraction to quality concerns, including elevated salinity and geogenic contaminants in deeper zones. Works focusing on western Haryana quantify overdrafts nearing 132 percent in aggregated blocks, underscoring mismatches between demand from water-intensive rotations and natural replenishment capacities. Earlier district-specific inquiries mapped average water table recession from shallower levels in the late 20th century to depths approaching 50 meters in contemporary records, attributing acceleration to subsidized power access and expanding cultivated extents.

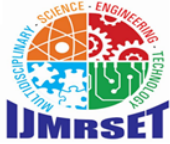
Collectively, prior scholarship establishes clear evidence of structural imbalances in Mahendergarh's groundwater regime, driven by physiographic constraints and anthropogenic pressures. Yet, many studies remain oriented toward broader state or multi-district scales, with limited integration of localized socioeconomic feedbacks or empirical testing of recharge interventions under variable climatic conditions. The present work extends these foundations through targeted spatio-temporal synthesis and context-specific management recommendations tailored to the district's fractured aquifers and agrarian context.

III. PROFILE OF THE DISTRICT

Mahendergarh district occupies the southern extremity of Haryana, sharing boundaries with Bhiwani, Charkhi Dadri, and Rewari to the north and northeast, while adjoining Alwar and Jhunjhunu districts of Rajasthan to the south and west. Spanning a geographical area of approximately 1,899 square kilometers, the district is administratively divided into two subdivisions—Mahendergarh and Narnaul—and comprises eight development blocks: Ateli, Kanina, Mahendergarh, Nangal Choudhary, Narnaul, Sihma, Nizampur, and Satnali. It encompasses 370 villages and five towns, reflecting a predominantly rural character with limited urban sprawl.

The topography is characterized by undulating plains interspersed with rocky outcrops and residual hills associated with the Aravalli ranges, particularly along the southern and southwestern fringes. Elevations generally range between 265 and 444 meters above mean sea level, with slopes varying from gentle in the plains to moderately steep (5–7 degrees) near the hillocks. This physiographic setting promotes rapid surface runoff and constrains the formation of extensive canal networks, rendering the district heavily dependent on subterranean resources for water needs.

Climatically, Mahendergarh experiences a tropical semi-arid regime influenced by its proximity to the Thar Desert. The district exhibits pronounced seasonal contrasts: scorching summers with mean maximum temperatures reaching 40–45°C in May and June, accompanied by hot, dust-laden loo winds; mild winters with occasional dense fog; and a short monsoon period. Annual rainfall averages 300–500 mm, highly erratic in distribution and intensity, with over 80 percent occurring



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during the southwest monsoon from June to September. Such variability severely limits consistent natural recharge to aquifers and heightens vulnerability to drought spells.

Geologically, the area features a heterogeneous substrate dominated by consolidated formations, including fractured crystalline rocks of the Aravalli system and overlying alluvial and aeolian deposits. Aquifers primarily occur in weathered zones, fractured horizons, and sedimentary layers, where secondary porosity governs groundwater occurrence and yield. Soils are predominantly medium-textured, with loamy sand and sandy loam being widespread; these soils exhibit low water-holding capacity and moderate to poor infiltration rates, further restricting recharge potential. In several pockets, soils show deficiencies in organic matter and essential nutrients, necessitating careful management for sustained productivity.

Agriculture forms the backbone of the local economy, engaging the majority of the workforce and contributing significantly to district income. The net sown area constitutes a large share of the total geographical extent, with irrigation coverage relying almost exclusively on groundwater sources due to negligible surface water availability. Major crops include wheat and mustard in the rabi season, alongside bajra, pulses, and coarse cereals during kharif. Cropping intensity remains moderate compared to northern Haryana districts, reflecting water constraints. Livestock rearing complements crop production, with cattle, buffalo, and small ruminants supporting dairy and supplementary income for rural households. Population density is relatively low, yet growing pressure on finite land and water resources has intensified cultivation on marginal lands.

This unique combination of physiographic constraints, climatic aridity, and geological limitations defines Mahendergarh's hydrogeological vulnerability. The district's limited canal command area and dependence on tube wells have shaped a resource extraction pattern that underscores the urgency of aligning agricultural practices with available recharge capacities. Understanding these foundational attributes provides essential context for analyzing observed groundwater trends and formulating targeted sustainability interventions suited to local conditions.

IV. APPROACH AND DATA HANDLING

The present investigation adopts a descriptive and analytical framework grounded in secondary hydrogeological and resource assessment datasets to examine groundwater level trends and associated sustainability challenges in Mahendergarh district. Quantitative evaluation of depletion patterns relies primarily on long-term monitoring records compiled by the Central Ground Water Board (CGWB) and the Ground Water Cell of the Haryana Irrigation and Water Resources Department. These agencies maintain a network of observation wells, including dug wells, tube wells, and piezometers, monitored biannually during pre-monsoon (May/June) and post-monsoon (October/November) periods.

Water level data spanning multiple decades up to the latest available assessment cycles form the core dataset. Depth to water table measurements from representative wells distributed across the eight development blocks provide the basis for district-wide and block-level trend analysis. Dynamic groundwater resource estimations, conducted jointly by CGWB and state agencies following the Ground Water Estimation Committee (GEC) methodology (with periodic updates), supply critical parameters such as annual recharge, extractable resources, gross draft for irrigation and domestic uses, and stage of groundwater extraction. These assessments classify blocks into safe, semi-critical, critical, or over-exploited categories based on extraction relative to replenishable resources.

Analytical procedures involve computation of long-term fluctuations by comparing historical baselines with contemporary readings to quantify cumulative declines. Spatial variability is assessed through block-wise aggregation of mean depths, percentage of area under different depth categories (e.g., below 30 meters), and extraction stages. Seasonal recovery rates are derived from pre- and post-monsoon differentials to evaluate recharge efficacy under prevailing climatic and geological conditions. Percentage changes in water levels over selected intervals, along with categorization shifts across successive assessment years, help identify accelerating or stabilizing trends in specific administrative units.

Data validation incorporates cross-verification between CGWB national compilations and state hydrogeological reports to ensure consistency. Where observation wells show abandonment or drying, supplementary piezometer records supplement the analysis. Cartographic representation through GIS platforms facilitates visualization of depth contours, fluctuation maps, and extraction hotspots, enabling identification of vulnerable pockets influenced by topographic and land-use factors.



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This approach ensures a robust, evidence-based synthesis that integrates quantitative metrics with contextual hydrogeological understanding. By focusing on official, periodically updated monitoring networks, the methodology maintains reliability while allowing for clear delineation of spatio-temporal depletion dynamics essential for formulating targeted management responses. All interpretations remain confined to observed patterns and standard resource evaluation norms without extrapolation beyond the compiled records.

V. PATTERNS OF AQUIFER DEPLETION

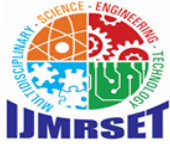
Groundwater levels in Mahendergarh district have exhibited a persistent downward trajectory over recent decades, driven by structural imbalances in the local hydrological balance. Comprehensive monitoring through a network of observation wells reveals that the district-averaged depth to water table stood at approximately 50.93 meters below ground level in 2023 assessments. This figure represents a marked recession from relatively shallower conditions documented in earlier baseline periods, underscoring the cumulative impact of sustained overdraft. Spatial distribution analysis indicates that over 81 percent of the district's geographical extent now falls within the extremely deep category, defined as depths exceeding 30 meters below ground level. Such extensive coverage of deep water table regimes signals widespread aquifer stress, transforming previously accessible resources into zones requiring deeper and more energy-intensive extraction.

Block-wise examination uncovers significant heterogeneity in depletion intensity, reflecting variations in geological setting, cropping patterns, and abstraction density. Ateli Nangal, Satnali, and Mahendergarh blocks have recorded the most severe cumulative declines, surpassing 30 meters from 1991 to 2023. These administrative units, characterized by higher tube-well concentrations and intensive agricultural activity, demonstrate accelerated recession rates that consistently outpace natural recharge processes. In contrast, Narnaul and Sihma blocks display comparatively moderated trends, with evidence of partial stabilization during the most recent decade, potentially attributable to lower extraction pressures or occasional favorable recharge episodes linked to localized rainfall variability. Intermediate patterns emerge in Kanina, Nangal Chaudhary, Nizampur, and other segments, where recession remains notable yet exhibits nuanced fluctuations influenced by site-specific hydrogeological attributes.

Temporal analysis of seasonal data further elucidates the limited resilience of the aquifer system. Pre-monsoon depths routinely register higher values than post-monsoon counterparts, yet the magnitude of seasonal recovery remains modest across most observation points due to constrained infiltration through predominant loamy sand and rocky formations. Individual monitoring stations document pre-monsoon levels ranging from 18.9 meters to beyond 112 meters below ground level in recent cycles, with several piezometers in southern and central locales approaching or exceeding 100 meters. Long-term fluctuation trends derived from decadal comparisons highlight average annual declines exceeding one meter in vulnerable pockets, with accelerated rates observed during periods of below-normal monsoon precipitation. These patterns align closely with the district's semi-arid climatic regime, where erratic rainfall distribution fails to compensate for high evapotranspiration and abstraction demands.

Dynamic resource assessments conducted under standardized Ground Water Estimation Committee protocols classify multiple blocks as over-exploited. Kanina registers extraction stages approaching 196 percent of annual recharge, followed by Mahendergarh at around 128 percent and Ateli Nangal at 121 percent. Nangal Chaudhary and Narnaul, previously categorized as safe or critical in earlier evaluations, have transitioned to over-exploited status in successive assessments, reflecting a progressive darkening of resource categorization. Overall district-level extraction hovers near or above 100 percent of replenishable resources, with net groundwater draft consistently surpassing availability in several units. This over-draft scenario persists despite regulatory awareness, manifesting in reduced future availability for irrigation and domestic needs while elevating operational costs for farmers reliant on deepening wells.

The spatial configuration of depletion correlates strongly with agricultural intensity and physiographic features. Hotspots of pronounced recession coincide with undulating plains supporting water-demanding crop rotations, whereas pockets near residual hillocks occasionally exhibit marginal buffering through secondary porosity in fractured zones. Hydrographs from representative wells illustrate non-linear recession curves, with steeper slopes during drought years and modest flattening during above-average rainfall periods that nonetheless fail to restore pre-depletion baselines. Comparative evaluation against adjoining districts in southern Haryana reveals that Mahendergarh's depletion profile ranks among the more acute, attributable to its limited canal command area and greater dependence on fractured crystalline and alluvial aquifers with inherently lower storage coefficients.



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Sustainability implications arising from these patterns extend to multiple dimensions. Progressive deepening compromises well yields, increases energy requirements for pumping, and heightens the risk of aquifer dewatering in shallower weathered zones. Quality concerns compound quantitative stress, as deeper extraction accesses mineralized layers prone to elevated salinity and geogenic contaminants. The transition of extensive areas into critically depleted regimes threatens the foundational support for the district's agrarian economy, where groundwater sustains the majority of irrigated acreage. Without calibrated interventions, continued trends portend diminished cropping intensity, livelihood disruptions for smallholder communities, and reduced adaptive capacity to climatic variability.

In synthesis, the observed aquifer depletion patterns in Mahendergarh district manifest as a spatially heterogeneous yet temporally consistent process of resource exhaustion. Empirical records from national and state monitoring networks confirm a shift toward deeper, over-stressed conditions across the majority of blocks, with extraction stages frequently exceeding sustainable thresholds. These dynamics underscore the urgent imperative for demand-side management and supply augmentation strategies calibrated to local hydrogeological realities. Addressing the documented recession requires integrated approaches that reconcile agricultural productivity with aquifer replenishment potential, thereby mitigating risks to long-term water security in this semi-arid landscape.

VI. KEY FACTORS ACCELERATING LOSS

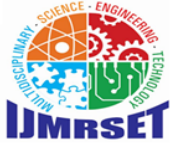
Several interconnected drivers have intensified groundwater recession in Mahendergarh district, creating a persistent imbalance between abstraction volumes and aquifer replenishment. Foremost among these is the overwhelming reliance on tube-well irrigation to sustain agricultural operations in the absence of reliable surface water infrastructure. With canal commands covering less than two percent of the irrigated area, more than 98 percent of cultivation depends on groundwater extraction through thousands of energized wells. This near-total dependence has accelerated since the post-Green Revolution period, as farmers expanded irrigated acreage to support higher-yielding varieties amid limited precipitation.

Intensive cultivation of crops with substantial water requirements further compounds extraction pressures. Although paddy cultivation remains less dominant than in northern Haryana, rotations involving wheat, mustard, and occasional cotton or other commercial crops demand repeated irrigation cycles, particularly during rabi and transitional seasons. Subsidized electricity for agricultural pumping has lowered the marginal cost of abstraction, encouraging deeper and more frequent withdrawals even in marginal lands. The proliferation of diesel and electric tube wells, often installed without adequate spacing norms, has resulted in competitive drawdown, where neighboring wells interfere and lower regional water tables.

Climatic and physiographic constraints severely restrict natural recharge, amplifying the effects of human-induced overdraft. Annual rainfall, averaging 300–500 mm and concentrated in the southwest monsoon, exhibits high inter-annual variability and frequent deficiency spells. Much of this precipitation is lost as surface runoff over the undulating terrain and rocky Aravalli fringes, where low-permeability formations and sandy loam soils with modest infiltration rates limit percolation to deeper aquifers. High evapotranspiration rates during the prolonged dry seasons further reduce available moisture for groundwater augmentation. Seasonal streams such as Dohan and Krishnawati carry episodic flows but contribute negligibly to sustained recharge due to their ephemeral nature and upstream interventions.

Geological characteristics of the district play a decisive role in modulating storage and transmission capacities. Aquifers occur predominantly in weathered residuum, fractured crystalline rocks of the Delhi Supergroup, and thin alluvial patches. Secondary porosity dominates, yielding variable and often modest transmissivity values that constrain both storage and lateral flow. In many locales, deeper extraction accesses mineral-rich layers, where prolonged rock-water interaction under semi-arid conditions elevates salinity and geogenic contaminants such as fluoride. These hydrogeological attributes render the system inherently less resilient to sustained pumping compared to thicker alluvial basins elsewhere in the state.

Emerging pressures from demographic and land-use shifts add incremental stress. Steady population growth and associated domestic demands, alongside modest expansion of built-up areas and infrastructure, have increased non-agricultural withdrawals. Conversion of fallow or pasture lands to cultivation has reduced natural vegetation cover that once facilitated localized infiltration. In the broader context of regional development, competing claims for limited water resources have reinforced the cycle of deepening dependence on subterranean sources.



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Collectively, these factors—structural irrigation dependency, policy-induced abstraction incentives, climatic aridity, geological limitations, and evolving land-use patterns—have driven extraction stages well beyond 100 percent of annual recharge in multiple blocks. The resulting acceleration of water table decline reflects not isolated influences but a systemic mismatch between resource availability and prevailing utilization practices. Addressing this acceleration necessitates targeted interventions that simultaneously moderate demand and enhance recharge potential within the district's distinctive environmental setting.

V. RAMIFICATIONS ON LOCAL SYSTEMS

The sustained decline in groundwater levels has generated cascading effects across agricultural, socioeconomic, and ecological domains in Mahendergarh district, undermining the foundational pillars of local stability. In the agricultural sector, deepening water tables have directly impaired irrigation reliability, compelling farmers to invest in progressively deeper tube wells and higher-capacity pumps. This escalation in extraction depth has elevated operational costs substantially, eroding profit margins for small and marginal landholders who constitute the majority of cultivators. Reduced well yields during peak demand periods have forced adjustments in cropping calendars, with delayed sowing or skipped irrigations leading to lower grain filling and diminished harvests of wheat, mustard, and other staples. Consequently, overall farm productivity has stagnated or declined in vulnerable blocks, threatening the district's contribution to regional food systems and exposing households to income volatility amid fluctuating market prices.

Socioeconomic repercussions extend beyond production metrics to influence livelihood security and community resilience. Rising energy expenditures for pumping have strained rural budgets, particularly in households already navigating thin economic margins. Many farmers report increased indebtedness linked to well-deepening loans, while others have shifted toward less water-demanding but lower-value crops, resulting in reduced household earnings. Labor migration has intensified in severely affected villages, as younger members seek off-farm opportunities in nearby urban centers or neighboring states, altering traditional family structures and depleting agricultural workforce availability. Women, who often manage domestic water collection and livestock care, face heightened burdens when hand pumps and shallow sources dry up, leading to longer travel distances for fetching water and potential compromises in hygiene and nutrition. These dynamics exacerbate existing inequalities, with resource-poor families experiencing disproportionate impacts on health, education, and overall well-being.

Domestic water supply systems have also suffered notable disruptions. Villages dependent on groundwater for drinking and sanitation encounter intermittent shortages, especially during pre-monsoon months when levels reach their annual lows. Public schemes relying on tube wells frequently require augmentation or relocation, incurring additional infrastructure costs for local administrations. In pockets where quality degradation accompanies quantitative depletion, elevated salinity or geogenic elements have rendered some sources less suitable for potable use, necessitating reliance on alternative—often distant or costly—supplies. Such unreliability not only affects daily routines but also heightens vulnerability to water-borne ailments, placing additional pressure on limited public health facilities.

Ecological consequences manifest in the degradation of local ecosystems and biodiversity support functions. Diminishing baseflows to seasonal streams and wetlands have reduced habitat availability for native flora and fauna, including migratory birds that utilize temporary water bodies. Lowered water tables have induced stress on deep-rooted vegetation and agroforestry species, contributing to gradual shifts in land cover toward more xeric communities. Soil moisture deficits in the root zone have accelerated erosion on undulating slopes, while reduced aquifer pressure may eventually trigger localized subsidence or compaction in alluvial pockets. These changes erode the district's natural buffering capacity against drought and extreme weather, creating feedback loops that further intensify resource stress.

At the community level, the interplay of these ramifications has fostered heightened competition over remaining water resources, occasionally sparking disputes among neighboring farmers or between agricultural and domestic users. Traditional water-sharing norms have weakened under scarcity conditions, while collective action for conservation remains fragmented due to varying impact severity across villages. The cumulative strain challenges the long-term viability of rural economies, potentially accelerating unplanned urbanization and diminishing the district's role as a stable agrarian hub within Haryana.



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In essence, the ramifications extend far beyond hydrological metrics, permeating productive systems, social fabrics, and environmental integrity. Without strategic reversal measures, these interconnected impacts risk entrenching cycles of decline that compromise sustainable development objectives for current and future generations in Mahendergarh.

VI. VIABLE PATHWAYS TOWARD BALANCE

Restoring equilibrium in Mahendergarh district's groundwater regime requires a multifaceted strategy that simultaneously curbs excessive extraction and augments recharge while aligning agricultural practices with local hydrological limits. Precision irrigation technologies, particularly drip and sprinkler systems, offer immediate potential to enhance water-use efficiency. By delivering water directly to crop root zones, these methods can reduce application losses by 40–60 percent compared to conventional flood irrigation, enabling farmers to maintain yields with substantially lower withdrawals. Targeted subsidies and demonstration plots in high-depletion blocks such as Ateli and Satnali could accelerate adoption among smallholders.

Crop diversification and adjustment of planting schedules represent another critical lever. Shifting from water-intensive wheat-mustard rotations toward drought-tolerant and low-water-footprint alternatives—including millets, pulses, oilseeds, and agroforestry species—would ease demand pressure on aquifers. Introduction of short-duration varieties and adoption of conservation agriculture techniques, such as zero tillage and mulching, can further conserve soil moisture and improve infiltration. Policy incentives, including minimum support prices for alternative crops and training programs through Krishi Vigyan Kendras, would facilitate this transition without compromising farmer incomes.

Engineered recharge structures tailored to the district's undulating terrain and fractured geology hold significant promise. Construction of check dams, percolation tanks, and farm ponds in suitable micro-watersheds can capture monsoon runoff that currently flows away unused. In rocky zones, rooftop rainwater harvesting combined with recharge shafts can inject harvested water directly into deeper fractured aquifers. Revival and desilting of traditional water bodies, alongside contour bunding on slopes, would enhance localized infiltration while reducing soil erosion. Integration of these structures with watershed development programs under schemes such as Mahatma Gandhi National Rural Employment Guarantee Act could generate employment while building climate-resilient infrastructure.

Demand-side governance measures must complement supply-side interventions. Rationalization of electricity subsidies through volumetric metering or time-of-day tariffs would discourage wasteful pumping and encourage efficient usage. Enforcement of well-spacing norms and mandatory registration of new tube wells in over-exploited blocks can prevent further competitive drawdown. Community-led aquifer management committees at the village level, involving farmers, panchayats, and local experts, would foster collective decision-making on extraction limits and equitable sharing protocols. Capacity-building initiatives focusing on water budgeting and crop-water requirement calculations can empower stakeholders to make informed choices.

Institutional coordination and monitoring enhancements form the backbone of effective implementation. Convergence of efforts among departments of irrigation, agriculture, rural development, and panchayati raj is essential to avoid fragmented initiatives. Deployment of additional piezometers and real-time telemetry in critical zones would enable dynamic tracking of water levels and early warning of stress escalation. Integration of remote sensing and GIS tools for periodic recharge potential mapping can guide prioritization of interventions. Public awareness campaigns utilizing local media and school programs would cultivate a conservation ethic across generations.

Long-term sustainability also demands integration of climate adaptation perspectives. Development of drought-resistant crop portfolios and insurance mechanisms linked to groundwater status would buffer farmers against rainfall variability. Exploration of conjunctive use—where limited surface water from seasonal streams is combined with groundwater—could optimize resource allocation during wetter periods. Research partnerships with agricultural universities could pilot innovative techniques such as artificial recharge using treated wastewater or managed aquifer recharge in suitable formations.

Implementation must proceed in a phased and participatory manner, beginning with pilot projects in the most stressed blocks and scaling successful models district-wide. Financial support through central and state schemes, coupled with private sector involvement in technology dissemination, would ensure viability. Regular impact assessments measuring changes in water levels, cropping patterns, and farmer incomes would allow adaptive management and course corrections.



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By pursuing these interconnected pathways—efficiency improvements, crop shifts, recharge enhancement, governance reforms, and institutional strengthening—Mahendergarh district can transition toward a more balanced groundwater regime. Such an approach not only safeguards the aquifer resource but also strengthens rural livelihoods, ecological health, and overall resilience in this water-stressed landscape.

VII. SYNTHESIS AND FORWARD PATH

The analysis of groundwater conditions in Mahendergarh district reveals a clear pattern of progressive aquifer depletion rooted in chronic over-extraction relative to limited recharge capacity. District-wide water tables have deepened to an average of approximately 50.93 meters below ground level, with more than 81 percent of the area classified under extremely deep categories. Multiple blocks exhibit extraction stages exceeding 100 percent of annual replenishable resources, with cumulative declines surpassing 30 meters in several high-stress zones since the early 1990s. These quantitative trends arise from a combination of near-total dependence on tube-well irrigation, water-intensive cropping systems, subsidized energy policies, erratic semi-arid rainfall, and geological formations that constrain natural infiltration. The resulting stress has manifested in elevated pumping costs, reduced agricultural reliability, threats to domestic water security, and degradation of supporting ecosystems.

Synthesizing these elements demonstrates that the sustainability challenge in Mahendergarh transcends isolated hydrological imbalance. It represents a systemic mismatch between prevailing land-use practices and the district's inherent resource endowment, where physiographic constraints amplify anthropogenic pressures. Socioeconomic ramifications, including income instability for smallholders, increased migration, and gender-differentiated burdens in water access, underscore the human dimension of aquifer decline. Ecological feedbacks, such as diminished baseflows and heightened erosion risk, further erode long-term resilience. Collectively, the evidence points to an urgent need for transformative rather than incremental adjustments if the district is to maintain its agrarian foundation while adapting to climatic variability.

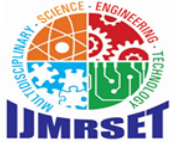
Looking forward, the pathway toward balance demands integrated action across efficiency, recharge, governance, and behavioral domains. Priority must be accorded to widespread adoption of micro-irrigation systems coupled with shifts toward low-water-footprint crops and improved agronomic practices. Parallel investments in watershed structures—check dams, percolation tanks, and rooftop harvesting—can meaningfully enhance recharge in suitable micro-catchments. Governance reforms, including rationalization of electricity tariffs, strict well-spacing regulations, and community-managed extraction protocols, will be essential to moderate demand. Strengthening institutional convergence and real-time monitoring will enable adaptive responses grounded in accurate data.

Successful reversal of current trends hinges on participatory implementation that engages local communities as primary stakeholders. Pilot initiatives in the most depleted blocks, supported by targeted financial incentives and technical extension services, can generate demonstrable results and build momentum for wider replication. Long-term success will also require embedding climate considerations into planning, such as drought-resistant cropping portfolios and conjunctive water use where feasible. Continuous evaluation through updated water level records and impact assessments will allow refinement of strategies over time.

In conclusion, Mahendergarh district stands at a critical juncture where timely and coordinated interventions can avert deeper crisis and secure sustainable water futures. By aligning agricultural development with aquifer limits and harnessing both traditional knowledge and modern technologies, the district can chart a resilient trajectory. This integrated approach not only addresses immediate depletion risks but also contributes to broader goals of rural prosperity, ecological balance, and water security in semi-arid regions of India. The coming years will test the collective resolve to translate diagnostic insights into actionable stewardship of this vital resource.

VIII. CONCLUSION

The groundwater situation in Mahendergarh district highlights the critical sustainability challenges facing semi-arid regions of southern Haryana. Long-term monitoring records indicate a steady decline in aquifer levels, with the district-averaged depth reaching approximately 50.93 meters below ground level and over 81 percent of the area classified under extremely deep categories. Several blocks have witnessed cumulative declines exceeding 30 meters since the early 1990s, while extraction stages in many units consistently surpass 100 percent of annual recharge. These patterns result from



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heavy dependence on tube-well irrigation, water-intensive cropping systems, subsidized electricity policies, erratic rainfall, and geological limitations that restrict natural replenishment.

The impacts of continued depletion are far-reaching, affecting agricultural productivity, household incomes, domestic water availability, and local ecosystems. Rising extraction costs and declining well yields threaten the viability of smallholder farming, while ecological degradation reduces landscape resilience to drought and climate variability.

Reversing these trends requires integrated interventions, including precision irrigation, crop diversification, decentralized recharge structures, rationalized energy pricing, and community-based governance frameworks. Strengthened monitoring and institutional coordination will support adaptive management tailored to local conditions.

Ultimately, sustainable groundwater management in Mahendergarh demands a transition from exploitation to stewardship. Timely action by stakeholders can restore balance between extraction and recharge, safeguard rural livelihoods, and ensure long-term water security in this water-stressed district.

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