



RESEARCH ARTICLE

Socioeconomic consequences of groundwater depletion: A case study of Haryana

Bhoopendra Singh Raghav & Arpita Gaurav Rastogi*

Department of Agriculture Economics, School of Agricultural Sciences, GD Goenka University, Sohana, Gurugram 122 103, Haryana, India

*Correspondence email - arpita.rastogi@gdgu.org

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Abstract

Groundwater depletion presents a significant threat to agricultural sustainability in Haryana, one of India's most intensively cultivated states. This study investigates the socioeconomic and environmental consequences of declining groundwater levels by assessing their effects on the cost of cultivating rice and wheat, irrigation-related capital investments, rural migration and key ecological outcomes. Primary data were collected from 220 farmers across selected districts through structured surveys, supplemented by secondary data from official sources. Cost-of-cultivation analysis and Garrett ranking techniques were used to evaluate economic and environmental impacts. Results indicate that groundwater depletion increases cultivation costs by 5–10 %, primarily due to increased irrigation and energy expenditures associated with deeper groundwater extraction. Farmers in overexploited areas are making greater investments in borewells and pumping technologies, resulting in increased indebtedness and financial vulnerability, especially among smallholders. Water stress is closely linked to rural migration, as reduced farm viability compels households to pursue non-farm livelihoods. Major environmental concerns identified include land subsidence, soil salinisation, declining groundwater quality, wetland degradation and biodiversity loss. The study concludes that groundwater depletion represents a structural challenge to farm economics, rural livelihoods and ecological sustainability, underscoring the necessity for integrated water management, crop diversification and policy reforms.

Keywords: cost of cultivation; environmental consequences; groundwater depletion; irrigation investments; rural migration

Introduction

Groundwater has been a foundational pillar of post-Green Revolution agrarian development in north-west India, enabling intensive multi-cropping systems that sustained rapid growth in rice and wheat production and supported rural livelihoods. However, decades of largely unregulated tube-well expansion, coupled with energy subsidies and procurement incentives favouring water-intensive cereals, have produced a persistent and regionally concentrated decline in aquifer storage (1, 2). Haryana, one of India's most highly irrigated and agriculturally productive states, exemplifies this trajectory: multiple districts register rapid declines in groundwater levels, with government assessments classifying many administrative units as overexploited (3, 4). The resulting interactions among rising irrigation costs, farm investment behaviour, land-use choices, environmental degradation and rural livelihood strategies constitute a pressing socioeconomic and policy problem that demands rigorous investigation. A growing empirical literature demonstrates that groundwater depletion does more than raise pumping depths: it reshapes cropping intensity, production risk and farm profitability, with distributional consequences across farm sizes and villages. High-resolution analyses indicate that declining groundwater availability can substantially reduce winter cropping intensity, with estimated national declines of up to 20 % overall and much larger losses in critically depleted regions and that expansion of

surface canals alone will not fully substitute for the loss of well-based irrigation (5). Complementary spatial-optimisation studies show that the current geography of government procurement and the incentives that sustain rice-dominant cultivation in the northwest underpin much of the aquifer stress; furthermore, alternative procurement and cropping allocations could, in principle, reduce groundwater stress while preserving food security (6, 7).

For Haryana, these broader national patterns translate into concrete socioeconomic pathways. Empirical evidence from north-west India and Haryana-specific case studies link groundwater decline to (a) rising cost of irrigation and overall cost of cultivation as wells are deepened and pump capacities upgraded, (b) shifts in farm investment decisions and capital allocation toward more expensive extraction technologies or, conversely, withdrawal from irrigated farming when costs become prohibitive and (c) intensified environmental problems such as soil salinization, declining water quality and biodiversity loss in intensively cultivated areas (8–10). These environmental changes, in turn, affect agronomic productivity and production risks for major staple crops, particularly rice and wheat, thereby threatening rural incomes and food security in a state that contributes a disproportionately large share of national procurement.

Beyond farm-level financial impacts, groundwater

depletion can influence longer-term structural changes in rural economies. A literature bridging hydrology and socioeconomic analysis indicates that increasing irrigation costs and reduced cropping opportunities increase the opportunity cost of farming and can accelerate outmigration and transitions to non-farm labour among affected households, especially smallholders and landless labourers who lack capital to invest in deeper wells or efficient irrigation technologies (9, 11). These shifts have distributional consequences: wealthier farmers may adapt by installing deeper wells or upgrading to electric pumps, while poorer households may face income losses or distress migration. In addition, groundwater extraction and pumping generate externalities including increased energy consumption and associated carbon emissions, underscoring the linkages between water use, energy subsidy policy and environmental externalities (6, 12).

Policy analyses underscore that the causes and solutions are multi-sectoral. Institutional and incentive structures, such as electricity pricing regimes, procurement policies and fragmented groundwater governance, are central to both the emergence of depletion and possible mitigation strategies (2, 13). Haryana's policy experiments with conservation, canal expansion and alternatives for rice cultivation provide an important applied laboratory for evaluating interventions (4). Yet modelling and empirical studies caution that supply-side interventions alone (e.g., canals) will be insufficient; demand-side measures (crop diversification, pricing reform and targeted recharge) and carefully designed social protections for vulnerable households are essential (5, 7, 8, 14). Given these linkages, this study addresses three interrelated objectives tailored to Haryana: (1) quantify how declining groundwater affects the cost of cultivation for the principal rabi and kharif staples, rice and wheat; (b) assess impacts on irrigation-related investments and consequent effects on rural migration; and (c) evaluate environmental consequences that mediate socioeconomic outcomes.

Materials and Methods

Study area

The study was conducted in Haryana, a state in northwestern India (Fig. 1). Although Haryana occupies only 1.4 % of India's land area, it plays a disproportionately large role in the nation's food grain supply, particularly in rice and wheat production. Since the Green Revolution, the state has emerged as a food surplus region, contributing significantly to India's food security. However, this success has been achieved at the cost of severe stress on natural resources, especially groundwater.

Data and sampling framework

The study utilised both primary and secondary data to ensure comprehensiveness and validity through triangulation. The primary data were collected through field surveys of 220 farmers using structured questionnaires following the given sampling framework (Fig. 2).

Sampling strategy

The study employed a multistage stratified purposive sampling design to capture spatial variations in groundwater depletion and its associated socioeconomic and environmental consequences across Haryana.

In the first stage, districts were selected purposively based on the groundwater exploitation status reported by the Central Ground Water Board (CGWB), ensuring representation from overexploited, critical and semi-critical categories. Additional criteria included dominance of the rice-wheat production system, high dependence on groundwater irrigation and documented evidence of declining groundwater levels.

In the second stage, two blocks from each selected district were chosen purposively to represent intra-district variation in groundwater stress and irrigation intensity. Selection was guided by block-level groundwater depth data, irrigation dependence and cropping patterns obtained from district statistical records.



Fig. 1. Administrative boundaries and districts of Haryana. Source: <https://paintmaps.com/map-charts/246c/Haryana-map-chart>.

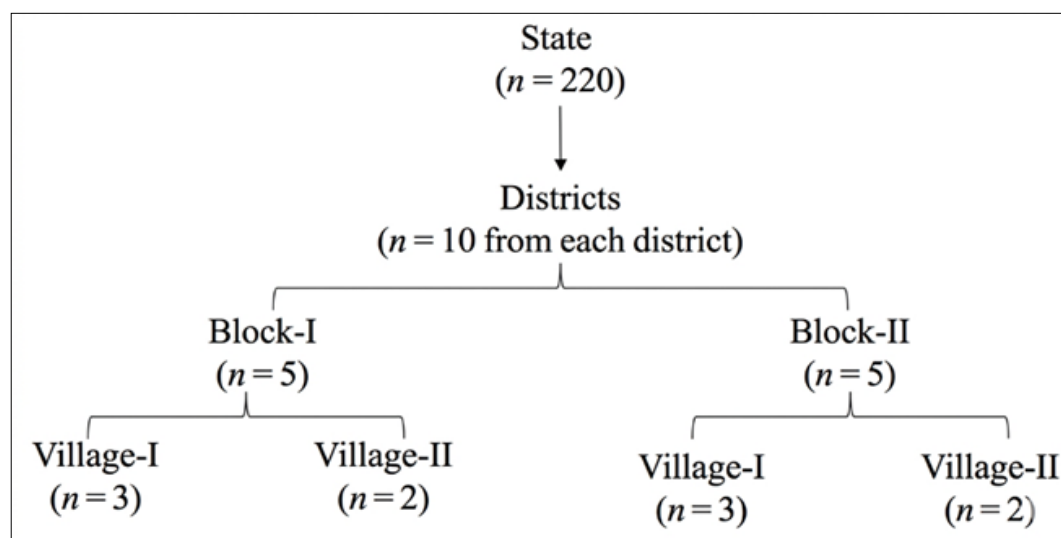


Fig. 2. Sampling framework adopted for the study.

In the third stage, two villages from each block were selected using a stratified random sampling approach, wherein villages were first stratified based on the source of irrigation (groundwater-dominated versus mixed irrigation systems).

In the final stage, farm households were selected through simple random sampling from village-level farmer lists. A uniform sample of 10 farmers per district was adopted, with five farmers selected from each block, distributed across villages as three from Village I and two from Village II.

The study covered 220 farm households, evenly distributed across the selected districts. The combination of purposive selection at higher administrative levels and random sampling at village and household levels ensured both contextual relevance and statistical representativeness, consistent with the study objectives. Secondary data was compiled from the key sources as mentioned in Table 1.

Methodology

To analyse the collected data, the study employed basic statistical tools, percentage analysis and tabular analysis. In addition, to assess the impact of groundwater depletion on the cost of cultivation of major kharif and rabi crops, namely rice and wheat, respectively, the study applied the cost of cultivation widely used across ground-level studies in India.

Cost A1 – It includes all actual expenses incurred by the owner in production, in cash and kind.

Cost A2 – Cost A1 + Rent paid for leased in land.

Furthermore, the Garrett ranking method was employed to assess farmers' perceptions regarding the consequences of groundwater depletion across different districts. The respondents' orders of merit were converted into ranks using the formula. To identify the most significant factor influencing the respondent, the Garrett ranking technique was used. According to this method, respondents have been asked to assign ranks to all pre-recorded constraints and the resulting rankings have been converted into a score using the formula in Eq. (1).

Table 1. Secondary data and their sources used in the study

S. No.	Variables	Data source
1.	District-wise groundwater statistics	Dynamic Ground Water Resources of Haryana State (various issues)
2.	Investments in irrigation	Economics of Farming in Haryana (various issues)
3.	District-wise rainfall	Economic Survey of Haryana 2022–23

$$R_{ij} = \frac{100 \times (R_{ij} - 0.5)}{N_j} \quad (\text{Eq.1})$$

Where R represents the rank given for the i^{th} variable by the j^{th} respondent, N denotes the number of variables ranked by the j^{th} respondent. The percentage position is converted to scores using the table provided by Garrett and Woodworth (11). Then, for each factor, the individual respondents' scores were summed and divided by the total number of respondents.

Results and Discussion

Cost of cultivation of rice and wheat in normal and groundwater-depleting regions

The analysis of cultivation costs for rice and wheat in normal and groundwater-depleting regions of Haryana highlights the economic impact of declining groundwater on crop production. In the case of rice, seed costs were higher in the groundwater-depleting region (INR 2745/ha) than in the normal region (INR 2550/ha), while fertiliser and micronutrient costs decreased slightly (INR 5000/ha vs INR 5250/ha). Plant protection chemicals increased moderately by 3.6 % in the depleted region. Tube-well irrigation costs were higher in groundwater-depleting areas (INR 750/ha vs INR 632.5/ha) and market irrigation costs showed a substantial increase of 26.5 % (INR 20562.5/ha vs INR 16250/ha). The imputed cost of tube-well operation on fuel was markedly higher in depleted regions (INR 53350/ha vs INR 41450/ha), indicating that deeper groundwater tables require greater energy expenditure. Hired labour costs were slightly lower (–2.3 %), while land rent decreased by 7.2 %, partially offsetting higher operational costs. Consequently, total paid costs (Cost A1) increased by 7.5 % and total economic costs, including ICT (Cost A2 + ICT), were 7.98 % higher in the depleted region (INR 161387.50/ha vs INR 149462/ha) (Table 2). These findings are consistent with previous studies reporting higher irrigation expenditures in groundwater-depleted regions due to increased pumping requirements (6, 15, 16).

Table 2. Cost of cultivation of rice and wheat (in INR/ha) in normal and groundwater-depleting regions

Inputs	Rice		Wheat	
	Normal region	Groundwater-depleting region	Normal region	Groundwater-depleting region
Seeds (INR/ha)	2550.00	2745.00	3200.00	3625.00
Fertiliser and micronutrients (INR/ha)	5250.00	5000.00	4875.00	5000.00
Plant protection chemicals (INR/ha)	4437.50	4597.50	2500.00	2810.00
Canal irrigation cost (INR/ha)	0.00	0.00	0.00	0.00
Tube-well irrigation (INR/ha)	632.50	750.00	105.00	112.00
Irrigation market cost (INR/ha)	16250.00	20562.50	2790.00	3437.50
Hired labour (INR/ha)	24142.00	23580.00	16250.00	17845.00
Land rent (INR/ha)	54750.00	50802.50	37500.00	36500.00
Imputed cost of tube-well (ICT) if run by fuel	41450.00	53350.00	6245.00	7885.00
Cost A1	53262.00	57235.00	29720.00	32829.50
Cost A2	108012.00	108037.50	67220.00	69329.50
Cost A2 + ICT	149462.00	161387.50	73465.00	77214.50

Source: Primary survey.

For wheat, similar patterns were observed, though the magnitude of cost differences varied. Seed costs increased by 13.2 % in groundwater-depleting regions (INR 3625/ha vs INR 3200/ha), while fertiliser and micronutrient costs were marginally higher (INR 5000/ha vs INR 4875/ha). Plant protection chemicals rose by 12.4 % in the depleted region. Tube-well irrigation and market irrigation costs increased moderately (INR 112/ha vs INR 105/ha and INR 3437.50/ha vs INR 2790/ha, respectively), whereas the imputed fuel costs for tube-well operations rose by 26.2 % (INR 7885/ha vs INR 6245/ha). Hired labour costs increased by 9.8 %, while land rent was slightly lower (-2.7 %). Consequently, total paid costs (Cost A1) were 10.4 % higher in depleted regions and total economic costs, including ICT (Cost A2 + ICT), increased by 5.1 % (INR 77214.50/ha vs INR 73465/ha). These results suggest that, as with rice, groundwater depletion increases wheat production costs, primarily through higher irrigation and labour costs (15, 16).

The observed patterns indicate that groundwater depletion not only increases operational costs but also affects farm profitability and input allocation strategies. The slight reduction in fertiliser costs for rice and the increase in labour costs for wheat reflect adaptive management strategies, such as modified input application or mechanisation, adopted to cope with water stress. The relatively smaller increase in irrigation costs for wheat compared with rice may be attributed to differences in crop water requirements, seasonal irrigation schedules and the utilisation of existing canal infrastructure. Overall, the findings underscore the need for sustainable water management interventions, including water-saving technologies such as direct-seeded rice (DSR), alternate wetting and drying (AWD) and efficient pumping systems, to mitigate the economic burden on farmers in groundwater-depleting regions (6, 17).

Farmers' investment in irrigation

The data on capital investments in irrigation across Haryana's

Table 3. Capital investments by farmers for irrigation in Haryana (INR)

Period	Central	Northern	Southern	Western	Total
2002–03	159232	227376	285584	203928	876120
2005–06	377512	1099016	528208	581832	2586568
2010–11	713784	2007504	575136	1264960	4561384
2015–16	1277000	1257176	1314136	827512	4675824
2020–21	1160780	1962168	326545	788574	4238067
2021–22	1188976	1984286	395546	797485	4366293
2022–23	1222030	2023914	366279	812637	4424860
Growth	10.73	11.55	1.25	7.16	8.43

Source: Based on Economics of Farming in Haryana (various issues).

agro-climatic zones between 2002–03 and 2022–23 reveal critical insights into the evolving dynamics of groundwater use and agricultural sustainability. At the state level, farmers' investments in irrigation infrastructure increased substantially from INR 876120 in 2002–03 to INR 4424860 in 2022–23, representing an overall growth of 8.43 % (Table 3). This sharp increase in capital expenditure underscores the increasing dependence on groundwater irrigation and reflects the growing financial burden borne by farmers to sustain agricultural production. The zonal distribution of investment further highlights the uneven pressures associated with groundwater depletion. The northern zone registered the highest growth rate (11.55 %), followed closely by the central zone (10.73 %), while the western zone recorded moderate growth (7.15 %). In contrast, the southern zone experienced negligible growth (1.25 %), indicating a relative stagnation of irrigation investments. These patterns closely align with the severity of groundwater depletion across regions. The northern and central zones are at the epicentre of the rice-wheat cropping system, which is highly water-intensive and heavily dependent on groundwater extraction. Continuous overextraction in these areas has led to widespread categorisation of blocks as "overexploited" by the CGWB (18). Farmers in these regions, therefore, are compelled to invest heavily in deep borewells, submersible pumps and other irrigation technologies to access declining water tables.

By contrast, the southern zone's low investment growth is linked to both hydrogeological and economic factors. Groundwater in southern Haryana is often brackish or saline, limiting its utility for crop cultivation. Consequently, farmers have fewer incentives to invest in costly irrigation infrastructure and agricultural intensification remains constrained. The western zone, though partially groundwater-dependent, benefits from supplementary canal irrigation, moderating the need for large-scale private investment compared with the northern and central

belts.

The socio-economic consequences of this rising investment trend are profound. First, higher irrigation costs translate into higher total cultivation costs, which disproportionately burden small and marginal farmers. While large farmers can finance bore well installation and benefit from economies of scale, smallholders often depend on groundwater markets, purchasing water at high rates from better-off farmers. This further exacerbates income inequality within rural communities, as the cost of accessing water rises while productivity gains remain uncertain. Second, recurring capital investments increase indebtedness among vulnerable farmers, pushing many into a cycle of financial distress. In extreme cases, this contributes to distress migration and withdrawal from farming as a livelihood activity.

Rural migration

To evaluate the implications of declining groundwater levels on rural migration, a structured survey was conducted among farming households across all districts of Haryana. A sample of 20 respondents was purposively selected from each district to capture variations in perceptions and experiences associated with water

scarcity. Table 4 presents the groundwater development status (State of Ground Water Dynamics – 2022 (SoGWD_2022)) across Haryana's districts, together with deviations in rainfall from normal levels, thereby providing important insights into the socioeconomic consequences of water scarcity, particularly rural migration. The data reveals a consistent trend: the severity of groundwater depletion and rainfall deficit is positively associated with people's perception of migration from rural areas towards urban centres or other livelihood sectors.

In critically affected and overexploited blocks such as Gurugram (Farukh Nagar and Pataodi, with –15 % rainfall deviation), Jind, Behal in Bhiwani and Murthal in Sonipat (–34 %), the perception of migration is among the highest, ranging from 50 % to 65 %. This indicates that the coincidence of hydrological stress (groundwater depletion) and climatic stress (negative rainfall deviation) coincides and the push factors for rural households to abandon agriculture and seek alternative livelihoods intensify. These findings are consistent with earlier studies emphasising that groundwater depletion in semi-arid regions directly contributes to livelihood vulnerability and migration (2, 19, 20). On the other hand, safe blocks such as Charkhi Dadri (–10 %), Hansi in Hisar (–3 %),

Table 4. The nexus between the water crisis and the perception of people on migration

District	Block	SoGWD_2022*	Rainfall deviation from 2021 (%)	Migration perception (%)
Ambala	Ambala-I	Critical	23	35
Ambala	Barara	Overexploited	23	30
Bhiwani	Bhiwani	Semi critical	–12	20
Bhiwani	Behal	Overexploited	–12	50
Charkhi Dadri	Badhra	Overexploited	–10	50
Charkhi Dadri	Charkhi Dadri	Safe	–10	10
Faridabad	Ballabgarh	Overexploited	–5	50
Faridabad	Tigaon	Overexploited	–5	50
Fatehabad	Bhuna	Critical	9	35
Fatehabad	Tohana	Overexploited	9	35
Gurugram	Farukh Nagar	Overexploited	–15	65
Gurugram	Pataodi	Overexploited	–15	65
Hisar	Hansi	Safe	–3	10
Hisar	Narnaul	Overexploited	–3	35
Jhajjar	Badli	Safe	–22	10
Jhajjar	Jhajjar	Safe	–22	10
Jind	Jind	Overexploited	–8	50
Jind	Julana	Safe	–8	10
Kaithal	Dhand	Overexploited	4	35
Kaithal	Siwan	Overexploited	4	35
Karnal	Nilokheri	Overexploited	21	30
Karnal	Indri	Critical	21	35
Kurukshetra	Ismailabad	Overexploited	37	30
Kurukshetra	Pipli	Overexploited	37	30
Mahendragarh	Mahendragarh	Overexploited	–4	35
Mahendragarh	Satnali	Critical	–4	35
Mewat	Nagina	Safe	5	10
Mewat	Touru	Overexploited	5	35
Palwal	Hathin	Safe	18	10
Palwal	Badoli	Overexploited	18	35
Panchkula	Barwala	Safe	43	10
Panchkula	Raipur Rani	Critical	43	35
Panipat	Bapoli	Overexploited	–10	50
Panipat	Samlakha	Overexploited	–10	50
Rewari	Bawal	Overexploited	–7	50
Rewari	Dahina	Critical	–7	35
Rohtak	Rohtak	Safe	–21	10
Rohtak	Maham	Safe	–21	10
Sirsa	Dabwali	overexploited	11	35
Sirsa	Rania	Overexploited	11	35
Sonipat	Gohana	Safe	–34	10
Sonipat	Murthal	Overexploited	–34	65
Yamunanagar	Chhachharauli	Safe	14	10
Yamunanagar	Bilaspur	Overexploited	14	35

Source: GoH, 2023 and primary survey. *SoGWD_2022: State of Ground Water Dynamics – 2022.

Badli and Jhajjar (–22 %) and Gohana in Sonipat (–34 %) exhibit very low migration perception levels (around 10 %). Despite rainfall variability, the availability of relatively secure groundwater resources buffers farm households against immediate livelihood shocks. This suggests that water availability acts as a stronger determinant of migration than rainfall fluctuations alone, highlighting that the vulnerability created by declining groundwater conditions undermines farm viability and compels households to diversify income sources.

Intermediate levels migration perceptions are observed in critical blocks such as Ambala-I, Bhuna in Fatehabad, Indri in Karnal and Dahina in Rewari, where responses average around 35 %. In these areas, the combination of declining groundwater tables and moderate rainfall deviations creates a sense of uncertainty, although the situation is not as severe as in overexploited regions. These results suggest a graded relationship between groundwater stress and migration, from safe and semi-critical to critical and overexploited, with perceptions of migration rising accordingly. From a socioeconomic perspective, the rising migration trend in overexploited areas reflects a structural transformation of rural livelihoods. As irrigation costs increase and water availability declines, farming becomes less profitable, pushing younger household members to migrate in search of non-farm opportunities. Such migration often leads to labour shortages in agriculture, feminisation of farming and reduced community cohesion in villages.

Furthermore, the results highlight that migration perceptions are not solely linked to water depletion but also shaped by rainfall variability. For instance, in Kurukshetra (Ismailabad and Pipli), despite better rainfall conditions, migration perceptions remain moderate (30 %), suggesting that structural groundwater depletion continues to outweigh short-term rainfall benefits. Conversely, in safe zones like Panchkula (Barwala, Raipur Rani), where migration perceptions have risen by +43 %, they remain low, underscoring that positive rainfall can reinforce resilience when coupled with sustainable groundwater use.

Environmental consequences of declining groundwater levels in Haryana

The Garrett ranking analysis presented in Table 5 provides critical insights into the ecological consequences of groundwater depletion in Haryana. The farmers were given eight different pre-recorded constraints (I: Decline in crop productivity; II: Reduced irrigated area; III: Soil salinisation and land degradation; IV: Decline in groundwater quality; V: Decline in wetland and pond ecosystems; VI: Reduction in biodiversity; VII: Land subsidence in overexploited aquifer zones; VIII: Increase in cost of irrigation and energy use), as mentioned in Table 5, for ranking. Based on the ranking assigned to each constraint and the corresponding Garrett score, it was found that, at the state aggregate level, the highest Garrett score was recorded for land subsidence in overexploited aquifer zones (52.05), indicating that farmers and local communities perceive this as the most severe and visible impact of unchecked groundwater extraction. Land subsidence has become a growing threat in several parts of Haryana, where excessive abstraction has destabilised aquifer structures and increased the risk of soil compaction. This not only reduces the long-term capacity of aquifers to store water but also results in irreversible damage to agricultural land. Similar observations have been reported in groundwater-stressed regions of India, such as Punjab and Uttar Pradesh, where continuous overextraction has led to structural deterioration of aquifers (18).

The second-highest ranked impact is the increase in irrigation and energy costs (50.78). This highlights the economic dimension of groundwater depletion, as farmers are compelled to invest more in deepening borewells and operating high-capacity pumps, which directly escalates energy consumption and production costs. Previous studies have similarly shown that groundwater depletion disproportionately affects small and marginal farmers, who face rising production costs without corresponding gains in productivity (2, 21). In Haryana, where agriculture is predominantly dependent on tube-well irrigation, this trend creates a vicious cycle: as water levels decline, farmers

Table 5. Garrett Score of perceived consequences of depleting the groundwater level

	Con-I	Con-II	Con-III	Con-IV	Con-V	Con-VI	Con-VII	Con-VIII
Ambala	53.20	39.70	48.30	52.10	49.90	48.60	55.90	51.30
Bhiwani	62.38	46.63	46.00	58.38	49.88	36.88	40.50	58.38
Charkhi Dadri	47.50	59.00	34.63	45.75	58.25	44.00	57.38	52.50
Faridabad	47.88	42.88	60.88	39.13	51.75	55.13	46.25	55.13
Fatehabad	56.38	61.63	55.00	39.75	45.63	48.38	50.75	41.50
Gurugram	46.75	52.25	51.75	60.00	49.63	46.75	49.63	42.25
Hisar	50.75	56.75	55.75	55.50	45.50	38.88	47.63	48.25
Jhajjar	52.38	41.38	54.88	41.25	54.25	56.63	50.88	47.38
Jind	45.63	49.25	47.88	48.13	44.25	64.88	48.38	50.63
Kaithal	54.63	53.38	47.63	48.13	47.38	49.13	49.13	49.63
Karnal	40.50	48.38	41.50	48.88	54.00	48.25	64.25	53.25
Kurukshetra	61.75	54.00	43.00	46.25	49.13	46.50	66.75	31.63
Mahendragarh	43.25	49.00	38.00	60.88	47.63	44.38	55.88	60.00
Mewat	40.00	52.38	59.88	45.25	54.13	46.63	48.38	52.38
Palwal	43.00	45.63	49.13	49.00	56.75	48.00	49.25	58.25
Panchkula	42.25	38.25	57.25	55.00	55.88	47.25	58.25	44.88
Panipat	61.00	50.88	48.75	41.38	46.50	55.88	47.38	47.25
Rewari	51.38	41.13	47.50	45.00	43.13	45.75	54.13	71.00
Rohtak	44.13	38.88	63.13	49.00	44.13	54.00	60.00	45.75
Sirsa	58.25	55.63	49.13	41.38	49.13	44.88	37.25	63.38
Sonipat	48.75	47.25	49.25	59.13	45.75	55.88	43.00	50.00
Yamunanagar	40.13	59.25	41.25	55.75	42.13	53.88	64.25	42.38
State score	49.63	49.25	49.56	49.32	49.30	49.11	52.05	50.78

Con-I: decline in crop productivity; Con-II: reduced irrigated area; Con-III: soil salinisation and land degradation; Con-IV: decline in groundwater quality; Con-V: decline in wetland and pond ecosystems; Con-VI: reduction in biodiversity; Con-VII: land subsidence in overexploited aquifer zones; Con-VIII: increase in cost of irrigation and energy use.

spend more on pumping, thereby increasing their vulnerability to indebtedness and reducing net farm income. Decline in crop productivity (49.63) ranked third among the most critical concerns. With shrinking water availability, farmers are unable to sustain water-intensive crops such as paddy and sugarcane, which dominate Haryana's agricultural system. Several respondents noted that yields of staple crops have been adversely affected, particularly in districts such as Bhiwani, Fatehabad and Sirsa, which are already under acute water stress. The linkage between groundwater depletion and declining productivity has been widely documented (1, 22), reinforcing the vulnerability of Haryana's farming systems.

Closely following these impacts were soil salinisation and land degradation (49.56) and the decline in groundwater quality (49.32). Both factors are interrelated, as over-extraction reduces freshwater recharge and accelerates the ingress of saline water, especially in western and southern Haryana. This not only affects soil fertility but also undermines the long-term sustainability of farming practices. Empirical evidence from the Indo-Gangetic Plains suggests that continuous groundwater stress exacerbates salinity hazards, rendering land unproductive over time (20). The ecological consequences extend further to a decline in wetland and pond ecosystems (49.30) and a reduction in biodiversity (49.11). Although ranked slightly lower, these outcomes highlight the broader environmental degradation linked to groundwater depletion. Reduced recharge and declining aquifer levels have contributed to the drying of wetlands, which are critical habitats for migratory birds and local biodiversity in Haryana. Over the years, shrinking wetlands such as those in Kurukshetra and Gurugram have been reported, signalling a disruption in ecosystem services that sustain both agriculture and rural livelihoods.

The close clustering of state-level Garrett scores, ranging from 49.11 to 52.05, suggests that groundwater depletion is not perceived as a single isolated issue but as a complex, interconnected problem affecting both farm productivity and ecological health. While land subsidence and irrigation costs reflect immediate and tangible concerns, ecological effects such as biodiversity loss, wetland decline and salinisation represent slower but equally damaging trends. The district-level variations, detailed in the annexure of this dissertation, illustrate how local hydrogeological and climatic conditions shape perceptions differently across Haryana.

Conclusion

This study highlighted the multifaceted socioeconomic and environmental consequences of groundwater depletion in Haryana, a state that plays a central role in India's food security. The findings demonstrate that declining water tables significantly increase cultivation costs for both rice and wheat, primarily through higher irrigation and energy expenditures. These rising costs reduce farm profitability, with disproportionate burdens falling on small and marginal farmers who often depend on costly groundwater markets. At the same time, farmers are compelled to make higher capital investments in bore wells and pumping technologies, further escalating indebtedness and financial vulnerability.

The evidence also underscores a growing linkage between water scarcity and rural migration. In overexploited districts,

households increasingly perceive farming as unsustainable, leading to livelihood diversification and migration toward non-farm opportunities. This transition not only reshapes rural labour markets but also risks widening socioeconomic inequalities.

Environmental impacts such as land subsidence, soil salinisation, loss of wetlands and declining biodiversity add another layer of risk, threatening long-term agricultural sustainability. Collectively, these findings demonstrate that groundwater depletion is not merely a hydrological issue but a structural challenge affecting livelihoods, ecosystems and food security. Sustainable solutions, therefore, require integrated policy interventions combining demand-side management, crop diversification, pricing reforms and social protection for vulnerable communities.

Future research should generate district-level water budgeting frameworks that integrate crop-wise water demand, groundwater recharge estimates and canal supply data to guide localised planning in Haryana. There is also a need for field-based experimental and pilot studies to evaluate the economic and hydrological impacts of specific interventions such as direct-seeded rice (DSR), micro-irrigation adoption, regulated electricity supply and incentive-based crop diversification away from paddy. Further, longitudinal household-level studies should be undertaken to assess how groundwater markets, rising irrigation costs and migration decisions evolve, particularly among small and marginal farmers in overexploited blocks.

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Authors' contributions

BSR conceptualised the study, conducted the field survey, performed data analysis and prepared the initial draft of the manuscript. AGR contributed to data interpretation, manuscript editing and critical revision of the content. Both authors have read and approved the final manuscript.

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