

Groundwater Depletion and Sustainable Water Resource Management in India

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1. Abstract

Groundwater is central to India's agricultural production, domestic water security and resilience to rainfall variability, yet intensive abstraction has created severe and spatially uneven sustainability pressures. This paper examines the scale, causes and consequences of groundwater depletion in India and evaluates pathways towards sustainable water-resource management. The study adopts a descriptive, analytical and comparative secondary-data design using the Central Ground Water Board's Dynamic Ground Water Resources Assessment 2025, groundwater-quality monitoring, Central Water Commission assessments, government programme documents and peer-reviewed research. The analysis is framed through the water–energy–food nexus and common-pool resource perspectives. The 2025 national assessment estimated annual groundwater recharge at 448.52 billion cubic metres (BCM), annual extractable resources at 407.75 BCM and annual extraction at 247.22 BCM, giving a national stage of groundwater extraction of 60.63%. However, this national average conceals acute regional stress: Punjab, Rajasthan and Haryana recorded extraction stages of 156.36%, 147.11% and 136.75%, respectively. Irrigation accounted for approximately 87% of total groundwater extraction, demonstrating the central role of agricultural demand. The paper finds that groundwater stress results from the interaction of water-intensive cropping systems, procurement and electricity incentives, hydrogeological constraints, climatic variability and fragmented governance. Although recent assessments show a declining proportion of over-exploited assessment units, long-term storage losses persist in major agricultural regions. Sustainable management therefore requires aquifer-specific water budgeting, crop diversification, incentive reform, efficient irrigation, managed recharge, conjunctive water use, community participation and strengthened monitoring. Groundwater policy must move beyond increasing supply towards managing demand within locally defined hydrogeological limits.

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2. Introduction

Groundwater has become one of the most strategically important natural resources in India. It supports irrigated agriculture, provides drinking water to large rural and urban populations, buffers agricultural production during weak monsoons and droughts, and enables economic

activity in areas where dependable surface-water supplies are limited. Its development contributed significantly to the expansion of irrigated agriculture after the Green Revolution because farmers could obtain water on demand rather than depend entirely on canal schedules or seasonal rainfall. The resulting groundwater economy, however, is characterised by millions of decentralised wells extracting from aquifers that differ greatly in recharge, storage and transmission capacity. Groundwater therefore combines enormous private benefits with a classic common-pool resource problem: an individual user receives most of the benefit of pumping while part of the cost of declining groundwater storage is transferred to other users and future generations (Shah, 2009; Sayre & Taraz, 2019).

India's latest national groundwater balance does not indicate uniform physical scarcity, but it reveals a major geographical mismatch between groundwater availability and abstraction. According to the Dynamic Ground Water Resources Assessment 2025, annual recharge was 448.52 BCM, annual extractable groundwater resource was 407.75 BCM and annual extraction was 247.22 BCM. The resulting national stage of extraction was 60.63%. Of 6,762 assessment units, 730 were classified as over-exploited, 201 as critical, 758 as semi-critical, 4,946 as safe and 127 as saline. The share of over-exploited units has fallen from 17.24% in 2017 to 10.80% in 2025, while safe units increased from 62.64% to 73.14%. These improvements are significant, but they should not be interpreted as evidence that India's groundwater problem has been resolved. Intensive depletion remains concentrated in highly productive agricultural and densely populated regions, and annual renewable-resource assessments do not measure groundwater-storage change in exactly the same way as long-term well observations or satellite gravimetry.

The sectoral composition of demand is particularly important. Of approximately 247 BCM of groundwater extracted annually in the 2025 assessment, about 215 BCM, or 87%, was attributed to irrigation; domestic uses accounted for about 28 BCM and industrial uses around 4 BCM. Groundwater depletion in India is consequently not only a hydrological problem. It is connected with agricultural policy, cropping patterns, food procurement, electricity pricing, farm incomes and climate adaptation. Mukherji (2022) conceptualises this interaction through the water–energy–food nexus: inexpensive or unmetered electricity lowers the marginal cost of pumping, agricultural support policies influence farmers towards particular crops, and groundwater provides the irrigation needed to sustain those cropping systems. Policies designed independently for food security, farm income and energy access can therefore produce cumulative pressure on aquifers.

The academic significance of this problem has increased further with evidence from satellite gravimetry and hydrological modelling. Rodell et al. (2009) identified substantial groundwater-storage depletion across north-western India during 2002–2008. More recent work indicates that climatic conditions can intensify these anthropogenic pressures. Mishra et al. (2024), combining observations, satellite data and hydrological modelling, estimated a net groundwater loss of about 450 km³ across northern India during 2002–2021 and found that monsoon drying combined with warmer winters can reduce recharge while increasing irrigation demand. These findings imply that groundwater, although traditionally considered a buffer against climate variability, can itself become less reliable when repeatedly used as the principal adaptation mechanism.

A research gap remains between assessments of national groundwater availability, studies of physical depletion and analyses of individual policy interventions. National averages may conceal local over-exploitation; satellite estimates capture changes in storage but do not by themselves explain institutional causes; and sector-specific solutions may underestimate linkages between agriculture, energy, climate and water governance. The present study therefore brings recent official groundwater assessments together with peer-reviewed hydro-climatic and socioeconomic evidence.

The study has four objectives: to evaluate the contemporary magnitude and spatial pattern of groundwater stress in India; to analyse the principal agricultural, energy, climatic and institutional drivers of depletion; to assess the socioeconomic and environmental implications of continuing groundwater decline; and to identify an integrated strategy for sustainable groundwater management. Correspondingly, it asks: How severe and geographically concentrated is groundwater stress in contemporary India? Which structural factors explain persistent over-abstraction? What consequences does depletion create for agricultural and water security? And which combination of demand management, recharge, institutional reform and community participation offers the most credible route towards sustainability? The central argument is that India's groundwater crisis cannot be addressed through artificial recharge or irrigation efficiency alone. Sustainable outcomes require simultaneous management of abstraction, crop choice, energy incentives, aquifer recharge and local governance.

3. Literature Review

The literature on Indian groundwater has evolved from concerns about agricultural groundwater development towards increasingly integrated analyses of depletion, governance and sustainability. Shah (2009) documented how the spread of individually controlled wells transformed South Asian irrigation. Groundwater provided flexibility, reduced dependence on centralised canal systems and created substantial agricultural benefits, but decentralised pumping also made conventional command-and-control regulation difficult. The resulting institutional problem is particularly severe because aquifers are shared while pumping decisions are largely private.

Satellite-based research established the physical scale of depletion. Rodell et al. (2009) used Gravity Recovery and Climate Experiment (GRACE) observations and land-surface modelling to estimate groundwater depletion of approximately $17.7 \pm 4.5 \text{ km}^3$ annually across Rajasthan, Punjab, Haryana and Delhi during 2002–2008. This study was influential because it demonstrated that depletion extended across administrative boundaries and could not be understood solely through isolated well observations. Asoka et al. (2017) subsequently showed that groundwater-storage variability reflects interactions between pumping and monsoon precipitation. Their analysis challenged simple explanations attributing all temporal groundwater change either to human withdrawal or to rainfall alone: precipitation affects recharge directly but can also affect pumping because farmers increase irrigation when rainfall is deficient.

Other studies have emphasised differences between aquifer systems. Bhanja et al. (2017) identified groundwater rejuvenation in some areas following changes in water-management policies, showing that groundwater decline is not necessarily irreversible. At the same time, the response of hard-rock aquifers in peninsular India differs from that of the deep alluvial aquifers

of the Indo-Gangetic region. Hard-rock aquifers generally have lower storage and can experience rapid seasonal depletion and recovery, whereas thick alluvial aquifers may sustain large withdrawals for long periods while accumulating substantial long-term storage losses. Consequently, indicators such as the number of dry wells, groundwater depth, annual groundwater balance and satellite-derived storage anomalies are related but not interchangeable.

The economic literature highlights the common-pool externality generated by unrestricted pumping. Sayre and Taraz (2019) demonstrate that declining groundwater can encourage repeated investment in deeper wells and stronger pumps, enabling individual farmers to preserve access while imposing additional costs on the wider aquifer system. This produces an inequitable technological race because wealthier farmers are more capable of deepening wells, while smallholders dependent on shallow sources may lose access earlier.

The water–energy–food nexus provides a broader policy framework. Mukherji (2022) argues that groundwater depletion is partly produced by interactions among agricultural pricing and procurement policies, electricity subsidies and water use. Chatterjee et al. (2024) provide more recent econometric evidence that output subsidies can reinforce cultivation of water-intensive crops. Their study associates guaranteed procurement with groundwater stress and estimates that rice procurement may account for at least half of the long-term decline in groundwater levels observed in Punjab in their study period. This does not imply that agricultural procurement is the sole cause of depletion; rainfall, hydrogeology, energy policy and farmers' risk considerations also matter. It does, however, demonstrate that groundwater outcomes cannot be separated from incentives affecting crop choice.

Research on food security likewise reveals an apparent paradox. Groundwater irrigation has supported high cropping intensity and reduced production risk, yet depletion now threatens the agricultural gains that groundwater helped create. Jain et al. (2021) estimate that continued depletion could substantially reduce cropping intensity and show that increased canal irrigation cannot fully replace the flexibility supplied by groundwater. Devineni et al. (2022) argue that geographically restructuring crop production and government procurement could reduce groundwater pressure while protecting food-security objectives. Crop-switching studies provide further support: Chakraborti et al. (2023) modelled cereal substitutions in parts of the Indo-Gangetic Plain and found that shifts towards less water-intensive cereals could generate substantial water savings together with gains in calorie production and farm profitability under their model assumptions.

Climate change adds another layer of uncertainty. Mishra et al. (2024) find that declining summer-monsoon rainfall in northern India and warmer winters can simultaneously reduce groundwater replenishment and increase irrigation requirements. This suggests an emerging feedback: farmers adapt to rainfall and temperature stress through additional groundwater pumping, but collective adaptation progressively weakens the groundwater reserve needed for future drought resilience.

The literature thus converges on three propositions. First, groundwater depletion is highly heterogeneous and must be understood at aquifer and sub-aquifer scales. Second, agricultural and energy policies strongly influence groundwater demand. Third, supply-side interventions alone are unlikely to achieve sustainability unless abstraction is simultaneously managed. The

unresolved policy question is how to translate these findings into an integrated framework capable of protecting farm livelihoods and food security without normalising continuous aquifer depletion.

4. Research Methodology

This study follows a descriptive, analytical and comparative secondary-data research design. No primary survey, interview, questionnaire or experimental dataset was used. The geographical scope is India, with particular attention to regions identified by official assessments and peer-reviewed research as having elevated groundwater stress.

The principal quantitative source is the National Compilation on Dynamic Ground Water Resources of India, 2025, prepared through the Central Ground Water Board (CGWB) and State/UT groundwater agencies. Its principal indicators are annual groundwater recharge, annual extractable groundwater resource, annual groundwater extraction, stage of groundwater extraction and assessment-unit classification. The stage of groundwater extraction is interpreted as the ratio of annual extraction to annual extractable groundwater resources. Official groundwater-quality reports, water-resource assessments and programme documents relating to aquifer mapping, groundwater regulation and participatory management are used as supplementary institutional evidence.

Peer-reviewed literature was selected to complement official resource accounting. GRACE/GRACE-FO studies, groundwater monitoring and hydrological modelling were used to evaluate long-term storage change, while agricultural economics and policy studies were used to investigate irrigation, subsidies, cropping systems and groundwater governance. The analytical framework combines the water–energy–food nexus with the concept of groundwater as a common-pool resource.

Data were compared across years only where the official assessments provided directly comparable indicators. State-level extraction stages were used to identify spatial contrasts, but they are not interpreted as uniform conditions within each state. Evidence from econometric or optimisation studies is reported as the finding of the respective studies rather than as observed national outcomes.

The methodology has several limitations. Dynamic groundwater-resource assessments evaluate renewable annual groundwater balances and are not identical to estimates of total aquifer storage derived from satellites or numerical models. State-level values can conceal significant intra-state variation. Secondary-data analysis cannot independently establish causality for all observed groundwater trends, and intervention outcomes vary according to rainfall, aquifer properties and implementation quality. These limitations are addressed by triangulating official assessments with multiple independent lines of peer-reviewed evidence.

5. Analysis and Discussion

5.1 Contemporary Magnitude and Spatial Pattern of Groundwater Stress

The 2025 assessment presents a mixed national picture. India's annual groundwater recharge was estimated at 448.52 BCM and its annual extractable resource at 407.75 BCM, compared with

total extraction of 247.22 BCM. Nationally, therefore, extraction represented 60.63% of the extractable resource. Yet sustainability cannot be inferred from this aggregate ratio because groundwater cannot be transferred freely from relatively underused aquifers to highly stressed ones.

Table 1. Selected groundwater indicators, India, 2025

Indicator	2025 value
Annual groundwater recharge	448.52 BCM
Annual extractable groundwater resource	407.75 BCM
Annual groundwater extraction	247.22 BCM
National stage of groundwater extraction	60.63%
Over-exploited assessment units	730 (10.80%)
Critical units	201 (2.97%)
Semi-critical units	758 (11.21%)
Safe units	4,946 (73.14%)
Saline units	127 (1.88%)

Source: Central Ground Water Board, Dynamic Ground Water Resources Assessment 2025.

Spatial contrasts are striking. Punjab recorded annual extraction of 26.27 BCM against an extractable groundwater resource of 16.80 BCM, producing an extraction stage of 156.36%. Rajasthan recorded 147.11% and Haryana 136.75%. Delhi stood at 92.10%, Puducherry at 75.98%, Tamil Nadu at 73.50% and Uttar Pradesh at 70.00%. Karnataka, at 66.49%, also exceeded the national average. These figures demonstrate why a national ratio below 100% is an inadequate sustainability criterion. A resource that is relatively abundant in Bihar, Assam or parts of eastern India cannot automatically compensate for chronic over-abstraction from an aquifer in Punjab or Rajasthan.

The nature of stress also differs geographically. In north-western alluvial aquifers, high agricultural withdrawals can exceed substantial natural recharge, producing persistent decline despite relatively productive aquifer systems. In arid western India, low recharge itself restricts the sustainable resource base. In peninsular hard-rock regions, aquifers often have limited storage, meaning that even moderate annual abstraction can create severe seasonal shortages and well failure. Management strategies therefore need to recognise hydrogeological heterogeneity rather than applying a uniform extraction threshold.

The improvement in official assessment-unit categories since 2017 remains noteworthy. Over-exploited units fell from 17.24% of assessment units in 2017 to 10.80% in 2025, while safe units increased from 62.64% to 73.14%. Recharge attributed to tanks, ponds and water-conservation structures also rose from 13.98 BCM in 2017 to 26.91 BCM in 2025. This suggests that conservation investments, rainfall conditions, changes in abstraction and improved recharge may produce measurable benefits.

However, these trends should be reconciled with satellite research reporting continuing storage loss in northern India. There is no necessary contradiction. Annual dynamic-resource assessments estimate replenishable groundwater flows and extraction, whereas GRACE-based studies estimate changes in terrestrial water storage over large spatial areas. An aquifer may show improved annual recharge or a lower extraction ratio while still carrying a legacy of substantial long-term storage depletion. Sustainable management should therefore monitor both annual water budgets and long-term groundwater levels/storage rather than treating either indicator as sufficient alone.

5.2 Agriculture, Electricity and the Water–Energy–Food Nexus

The dominance of irrigation in groundwater extraction identifies agriculture as the principal demand-management challenge. The 2025 assessment attributes about 215 BCM, or 87% of annual extraction, to irrigation, compared with around 11% for domestic use and 2% for industry. The implication is not that household and industrial conservation are unimportant, but that a national groundwater strategy that avoids changing agricultural water demand is unlikely to alter the overall groundwater balance substantially.

The historical spread of tube-well irrigation gave farmers an important form of production security. Unlike many canal systems, private groundwater allows irrigation to be timed according to crop requirements. This flexibility increased yields and facilitated multiple cropping, but it also transformed the incentive structure of water use. Where electricity for agriculture is free or supplied at flat rates, the marginal financial cost of pumping additional groundwater may be substantially below its social and environmental cost. Deeper groundwater tables may therefore result in stronger pumps and deeper wells rather than an immediate reduction in water demand.

The food-procurement system interacts with these energy incentives. Rice and wheat procurement helped India achieve food security, but long-term procurement concentration in water-stressed regions can reinforce cropping systems poorly matched to local water availability. Chatterjee et al. (2024) find evidence that output subsidies contributed to excessive production of water-intensive crops and estimate a substantial contribution of rice procurement to groundwater decline in Punjab. The relevant policy lesson is not that minimum support prices should simply be removed. Abrupt withdrawal could create severe livelihood risks. Instead, the geographic and crop composition of procurement needs gradual realignment so that farmers receive credible markets and income protection when moving towards less water-intensive crops.

Crop diversification is therefore a groundwater intervention as well as an agricultural policy. Modelling by Chakraborti et al. (2023) suggests that switching portions of rice and wheat cultivation towards millet, sorghum and other locally suitable cereals can reduce water consumption while potentially maintaining or improving food and farm-income outcomes. Their model estimated water-use reductions of approximately 32% under an optimised crop-switching configuration in the study region, although such results are scenario-dependent and should not be treated as guaranteed field outcomes.

Micro-irrigation can complement diversification by reducing applied irrigation water, particularly where crops and agronomic conditions are suitable. Yet irrigation-efficiency improvements must be interpreted carefully. If farmers use saved water to expand irrigated area

or shift towards more water-intensive production, reductions in water application per hectare may not translate into equivalent aquifer savings. Sustainable groundwater policy should therefore measure consumptive water use and total abstraction, not merely the efficiency of individual irrigation devices.

The strongest agricultural strategy consequently combines crop choice, irrigation scheduling, energy incentives and groundwater budgeting. Subsidies could increasingly reward measured water savings, crop diversification or energy conservation rather than simply reducing the private cost of pumping. Such reform would convert groundwater sustainability from an environmental restriction into an element of farm-risk management.

5.3 Climate Variability, Recharge and Aquifer Resilience

Groundwater is intimately linked with the monsoon. Rainfall replenishes aquifers directly through infiltration and indirectly through rivers, canals, tanks and irrigation return flows. At the same time, rainfall affects abstraction because weak monsoons lead farmers to compensate with additional pumping. Groundwater recharge and groundwater withdrawal are therefore dynamically connected.

Asoka et al. (2017) demonstrated that changes in monsoon precipitation explain a significant share of groundwater-storage variability across many regions of India, while also recognising the importance of pumping. This relationship becomes more consequential under climate change. Mishra et al. (2024) report an approximately 8% decline in summer-monsoon precipitation over northern India during 1951–2021 in their study and estimate groundwater depletion of around 1.5 cm per year during 2002–2021, corresponding to a net storage loss of approximately 450 km³. Their modelling indicates that future combinations of monsoon drying and winter warming could increase irrigation demand while reducing recharge.

This evidence challenges the assumption that groundwater can indefinitely function as an emergency reserve. During an isolated drought, groundwater pumping is a rational and valuable adaptation. But if droughts, warming and irrigation demand increase over repeated seasons, adaptation through pumping can progressively exhaust the reserve that makes adaptation possible. Sustainable groundwater policy must therefore preserve strategic aquifer storage for climatic extremes rather than manage groundwater solely according to average-year recharge.

Managed aquifer recharge can contribute to this objective. The official assessment indicates that recharge associated with tanks, ponds and water-conservation structures has risen considerably since 2017. Nevertheless, recharge interventions must be hydrogeologically targeted. A check dam or recharge shaft is effective only where water is available, water quality is suitable, geological conditions permit infiltration and the additional recharge is not simply followed by equivalent additional pumping.

Urban areas pose another challenge because paved surfaces reduce natural infiltration while water demand and groundwater extraction rise. Urban recharge should therefore integrate storm-water management, restoration of wetlands and water bodies, permeable surfaces, treated wastewater reuse and protection of natural recharge zones. Merely mandating rooftop rainwater-harvesting structures without monitoring their functionality provides limited assurance of aquifer recovery.

5.4 Consequences for Agriculture, Equity and Water Security

Declining groundwater creates effects well beyond hydrology. The most immediate agricultural consequence is increasing pumping depth. Greater lift increases energy requirements and may require farmers to replace centrifugal pumps with submersible systems, deepen borewells or drill new wells. These expenditures increase production costs even when electricity itself remains subsidised.

Access to deeper groundwater is also socially unequal. A large farmer may respond to a falling water table by investing in a deeper borewell, whereas a marginal farmer may lack the capital required. The latter can become dependent on purchasing irrigation water, reduce irrigated area or abandon a dry well altogether. Sayre and Taraz (2019) show how repeated well deepening can amplify the economic losses associated with the groundwater common-pool problem. Groundwater depletion is therefore capable of converting hydrogeological scarcity into unequal access to productive assets.

Agricultural production itself is vulnerable. Jain et al. (2021) estimate that continued depletion could reduce cropping intensity substantially, especially in already groundwater-depleted regions. Importantly, their analysis indicates that increasing canal irrigation does not fully substitute for groundwater because canal supplies and groundwater differ in timing, spatial coverage and reliability. Groundwater sustainability is thus directly connected to food security, but this relationship creates a strong reason for conservation rather than a justification for continued over-abstraction.

Water quality further complicates availability. The CGWB's national groundwater-quality monitoring identifies localised problems involving nitrate, fluoride, arsenic, salinity and other contaminants, although the distribution varies substantially between regions. The Annual Ground Water Quality Report 2024, for example, was based on 15,259 monitoring locations, illustrating the spatial complexity of the problem. Depletion can worsen quality risks in some settings by altering groundwater flow, encouraging deeper pumping or increasing salinity intrusion, particularly in coastal and arid environments. Quantity and quality management should therefore be integrated: an aquifer cannot be considered secure solely because physical water remains available if that water is unsuitable for drinking or irrigation.

Groundwater also supports river baseflow, wetlands and groundwater-dependent ecosystems. Persistent lowering of groundwater heads can reduce discharge from aquifers to surface-water systems. This means that excessive groundwater withdrawal can ultimately affect what appears to be a separate surface-water resource. The conventional administrative separation of groundwater and surface water is therefore inconsistent with hydrological reality.

5.5 Governance and Evaluation of Existing Management Initiatives

Groundwater governance in India is institutionally complex because water is primarily a State subject, while the Union Government provides regulatory, technical, financial and programme-level interventions. The Central Ground Water Authority operates under Section 3(3) of the Environment (Protection) Act, 1986 and regulates groundwater abstraction for specified industrial, infrastructure and mining activities in jurisdictions under its authority. National groundwater-extraction guidelines issued in 2020 and amended in 2023 include provisions

relating to water audits, abstraction/restoration charges, monitoring and environmental compensation.

Such regulation is stronger for formal industrial projects than for agricultural groundwater use. This asymmetry is understandable because regulating millions of farm wells individually would impose enormous administrative and political costs. Yet agriculture is responsible for the overwhelming majority of extraction. The governance challenge is therefore to regulate groundwater indirectly through institutions and incentives that influence collective behaviour rather than relying solely on well-by-well licensing.

The National Aquifer Mapping and Management Programme (NAQUIM) is important in this context because management requires knowledge of aquifer boundaries, storage properties and recharge characteristics. Government reporting indicates that the approximately 2.5 million km² mappable area targeted under the programme has been covered. The policy challenge now is to translate hydrogeological mapping into locally enforceable water budgets and land-use decisions rather than treating mapping as an end in itself.

Atal Bhujal Yojana represents a different institutional approach. The pilot programme covered 8,203 water-stressed Gram Panchayats in 229 blocks across 80 districts in Gujarat, Haryana, Karnataka, Madhya Pradesh, Maharashtra, Rajasthan and Uttar Pradesh and operated until October 2025. Its central features included groundwater-data disclosure, community water budgeting, Water Security Plans and demand-side interventions. This approach addresses a critical governance problem: groundwater users are more likely to understand collective limits when information is presented at a scale connected to local decisions.

The programme's significance lies less in any claim that community participation alone can reverse groundwater depletion and more in its demonstration that groundwater management can be decentralised without treating pumping decisions as purely private. The next step should be rigorous long-term evaluation of whether participatory water budgets produce measurable reductions in abstraction, stabilisation of groundwater levels and equitable distribution of costs and benefits under different rainfall conditions.

5.6 Framework for Sustainable Groundwater Management

The evidence suggests that no single intervention is sufficient. A sustainable groundwater strategy should begin with aquifer-based limits. Administrative boundaries are useful for governance but groundwater follows geological boundaries. Aquifer and sub-aquifer water budgets should establish recharge, sustainable abstraction ranges, groundwater-quality constraints and minimum strategic storage requirements. Assessment units should then be linked to these hydrogeological limits.

Second, demand management must become the core agricultural intervention. In severely over-exploited regions, expanding artificial recharge while leaving crop and pumping incentives unchanged risks producing a recharge-extraction cycle rather than recovery. Crop diversification should therefore be supported through assured procurement, extension services, value-chain infrastructure, processing facilities and income-risk protection. Punjab and Haryana cannot be expected to move away from water-intensive cropping through conservation messaging alone if market incentives continue favouring the existing system.

Third, electricity reform and groundwater policy should be integrated. Universal abrupt removal of farm-power subsidies would be socially and politically problematic. More workable approaches include feeder-level energy accounting, direct income support separated from electricity consumption, incentives for verified energy savings and programmes in which farmers share the financial benefits of electricity conserved. Solar irrigation requires particular care: although it can reduce carbon emissions and energy costs, zero-marginal-cost solar pumping may increase groundwater extraction unless surplus electricity can be sold back to the grid or pumping is otherwise constrained.

Fourth, irrigation efficiency should be evaluated at basin and aquifer scales. Drip and sprinkler irrigation remain valuable technologies, but programme evaluation should measure reductions in total groundwater abstraction rather than only hectares covered by micro-irrigation. Irrigation scheduling, soil-moisture management, laser land levelling where appropriate, mulching, agronomic improvements and deficit-irrigation strategies can complement hardware investments.

Fifth, managed recharge requires scientific targeting. Recharge structures should be selected on the basis of aquifer characteristics, water availability, water quality, catchment behaviour and expected recovery. Traditional tanks, ponds and wetlands can play important roles where their hydrological functions are protected. The increase in estimated recharge from tanks, ponds and conservation structures reported between 2017 and 2025 provides encouraging evidence that recharge interventions can contribute to national groundwater accounts, but their effectiveness must be assessed locally.

Sixth, surface water and groundwater should be managed conjunctively. Canal supplies can reduce dependence on groundwater in some regions, while groundwater can provide flexibility when surface supplies are temporarily inadequate. The objective should not be universal replacement of groundwater by canals but coordinated allocation that avoids both groundwater depletion and waterlogging.

Seventh, monitoring and transparency need strengthening. Groundwater-level observation networks, digital water-level recorders, remote sensing, extraction estimates and local well inventories should increasingly feed into publicly accessible decision systems. Resource assessments should report uncertainty and distinguish clearly among groundwater level, renewable resource, extraction stage and total storage change. This would reduce the tendency to interpret improvement in one indicator as universal groundwater recovery.

Finally, groundwater sustainability requires an equity principle. Restrictions that merely reduce access for small farmers while allowing capital-intensive users to drill deeper would be environmentally ineffective and socially regressive. Community water budgeting, targeted financial assistance for crop transition, protection of drinking-water sources and differentiated policies for marginal farmers should therefore be integral to groundwater reform.

6. Conclusion

Groundwater depletion in India is neither a uniform national shortage nor an isolated environmental problem. It is a spatially concentrated resource-governance challenge produced through interactions among aquifer characteristics, agricultural demand, energy incentives, food policy, urbanisation, rainfall variability and climate change. The 2025 groundwater assessment

offers evidence of both progress and continuing risk. National annual recharge reached 448.52 BCM against annual extraction of 247.22 BCM, and the proportion of assessment units classified as over-exploited has declined compared with 2017. Nevertheless, Punjab, Rajasthan and Haryana continue to extract groundwater at rates substantially greater than their annual extractable resources, while other regions face critical, semi-critical or quality-related constraints.

The first research question concerned the severity and spatial pattern of depletion. The evidence shows that national averages conceal extreme regional concentration. The second concerned its causes. Agriculture is dominant, accounting for approximately 87% of groundwater extraction, but the underlying drivers include more than irrigation itself: water-intensive cropping, procurement incentives, subsidised energy, decentralised private wells, climate variability and hydrogeological conditions interact to determine pressure on aquifers.

The third question addressed implications. Continued depletion increases well depth and energy requirements, disadvantages farmers unable to finance deeper wells, threatens dry-season cultivation and weakens groundwater's capacity to buffer drought. Groundwater-quality degradation and ecological impacts further reduce the effective resource available to society. Because surface and groundwater are hydrologically connected, depletion can also influence rivers, wetlands and associated ecosystems.

The final question concerned sustainable management. The evidence indicates that supply augmentation alone is insufficient. Artificial recharge, rainwater harvesting and surface-water infrastructure remain important, but their benefits can be offset where abstraction continues to rise. Demand-side management must therefore become equally prominent. Aquifer-based water budgeting, crop diversification, better alignment of food procurement with regional water availability, reform of electricity incentives, efficient irrigation, scientifically targeted recharge, conjunctive use and transparent groundwater monitoring should operate as complementary measures.

India's recent policy experience also demonstrates that groundwater governance need not rely exclusively on centralised regulation. Participatory approaches such as water budgeting and Water Security Plans provide mechanisms for converting an invisible underground resource into a collectively understood local constraint. Their long-term hydrological effectiveness, however, should be independently and consistently evaluated.

The broader policy principle is straightforward: groundwater should be managed as a renewable but finite common resource rather than an unlimited private input to agricultural and urban development. Sustainable management does not require ending groundwater use; groundwater is too important to Indian food and water security for such an approach. It requires ensuring that abstraction, over appropriate time horizons, remains compatible with recharge, strategic storage, water quality and ecological requirements.

Future research should combine high-resolution groundwater-level observations, remote sensing, well inventories, farm-level behavioural evidence and aquifer models to evaluate which combinations of incentives and conservation measures produce durable reductions in abstraction. Particular attention should be given to the distributional effects of reform on small and marginal farmers and to groundwater behaviour under increasing climatic extremes. Ultimately, India's

groundwater security will depend less on discovering new sources of water than on aligning agricultural production, energy policy and local economic development with the hydrological limits of its aquifers.

7. References

- Asoka, A., Gleeson, T., Wada, Y., & Mishra, V. (2017). Relative contribution of monsoon precipitation and pumping to changes in groundwater storage in India. *Nature Geoscience*, 10, 109–117. <https://doi.org/10.1038/ngeo2869>
- Bhanja, S. N., Mukherjee, A., Rodell, M., Wada, Y., Chattopadhyay, S., Velicogna, I., Pangaluru, K., & Famiglietti, J. S. (2017). Groundwater rejuvenation in parts of India influenced by water-policy change implementation. *Scientific Reports*, 7, 7453. <https://doi.org/10.1038/s41598-017-07058-2>
- Central Ground Water Board. (2025a). *National compilation on dynamic ground water resources of India, 2025*. Ministry of Jal Shakti, Government of India.
- Central Ground Water Board. (2025b). *Annual ground water quality report 2025*. Ministry of Jal Shakti, Government of India.
- Central Water Commission. (2024). *Assessment of water resources of India, 2024*. Ministry of Jal Shakti, Government of India.
- Chakraborti, R., Davis, K. F., DeFries, R., Rao, N. D., Joseph, J., & Ghosh, S. (2023). Crop switching for water sustainability in India's food bowl yields co-benefits for food security and farmers' profits. *Nature Water*, 1, 864–878. <https://doi.org/10.1038/s44221-023-00135-z>
- Chatterjee, S., Lamba, R., & Zaveri, E. D. (2024). The role of farm subsidies in changing India's water footprint. *Nature Communications*, 15, 8654. <https://doi.org/10.1038/s41467-024-52858-6>
- Devineni, N., Perveen, S., & Lall, U. (2022). Solving groundwater depletion in India while achieving food security. *Nature Communications*, 13, 3374. <https://doi.org/10.1038/s41467-022-31122-9>
- Jain, M., Fishman, R., Mondal, P., Galford, G. L., Bhattarai, N., Naeem, S., Lall, U., Balwinder-Singh, & DeFries, R. S. (2021). Groundwater depletion will reduce cropping intensity in India. *Science Advances*, 7(9), eabd2849. <https://doi.org/10.1126/sciadv.abd2849>
- Janardhanan, S., Nair, A. S., Indu, J., Pagendam, D., & Kaushika, G. S. (2023). Estimation of groundwater storage loss for the Indian Ganga Basin using multiple lines of evidence. *Scientific Reports*, 13, 1797. <https://doi.org/10.1038/s41598-023-28615-y>
- Ministry of Jal Shakti. (2023). *Consolidated guidelines to regulate and control ground water extraction in India: Notification dated 24 September 2020 with amendment dated 29 March 2023*. Government of India.

- Mishra, V., Dangar, S., Tiwari, V. M., Lall, U., & Wada, Y. (2024). Summer monsoon drying accelerates India's groundwater depletion under climate change. *Earth's Future*, 12(8), e2024EF004516. <https://doi.org/10.1029/2024EF004516>
- Mukherji, A. (2022). Sustainable groundwater management in India needs a water–energy–food nexus approach. *Applied Economic Perspectives and Policy*, 44(1), 394–410. <https://doi.org/10.1002/aepp.13123>
- Rodell, M., Velicogna, I., & Famiglietti, J. S. (2009). Satellite-based estimates of groundwater depletion in India. *Nature*, 460, 999–1002. <https://doi.org/10.1038/nature08238>
- Sayre, S. S., & Taraz, V. (2019). Groundwater depletion in India: Social losses from costly well deepening. *Journal of Environmental Economics and Management*, 93, 85–100. <https://doi.org/10.1016/j.jeem.2018.11.002>
- Shah, T. (2009). *Taming the anarchy: Groundwater governance in South Asia*. Resources for the Future Press.