

Strengthening Farmer-Led Strategies Against Groundwater Depletion in India's Climate-Vulnerable Farming Regions of Punjab.

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Abstract

Punjab, India's breadbasket, faces a dire groundwater crisis, with 78% of blocks classified as over-exploited due to the water-thirsty rice-wheat monoculture that consumes 80-90% of irrigation needs (Central Ground Water Board, 2024). Annual water table declines of 0.16 meters exacerbate climate vulnerabilities, including erratic monsoons, heightened greenhouse gas emissions from energy-intensive pumping, and threats to food security (Sharma et al., 2026). Excluded from national schemes like Atal Bhujal Yojana, Punjab requires urgent, farmer-led interventions to foster climate-resilient water management (Ministry of Jal Shakti, 2020). This study proposes a targeted Capacity Building Program to empower Punjab's 1.5 million farmers through multi-tiered training in Climate-Smart Agriculture (CSA). Drawing from proven models like MARVI (International Water Management Institute, 2021) and APFAMGS (Food and Agriculture Organization, 2024), the program emphasizes participatory groundwater monitoring, crop diversification to low-water millets, Direct Seeded Rice (DSR), micro-irrigation, Managed Aquifer Recharge (MAR), and regulated solar pumps with grid integration (Jadeja et al., 2018). Successful implementation of these initiatives involves phase-wise integration of various state partners like Punjab Agricultural University (PAU), CGWB, and NGOs such as TERI, alongside World Bank pilots (The Energy and Resources Institute, 2019). A 36-month timeline structure is proposed where Phase 1 (Months 1-3) for baseline surveys in hotspots like Jalandhar and Hoshiarpur will be initiated; Phase 2 (4-12) rolls out workshops for 10,000 farmers across 100 villages, with field demos shifting 20-30% cropping to resilient varieties; Phase 3 (13-24) scales cooperatives and app-based tracking; and Phase 4 (25-36) evaluates via audits, targeting 30% over-extraction cuts and sustained aquifer recharge (CEEW, 2023). Expected outcomes include bolstered resilience, reduced emissions, and economic viability through power sales and yield stability. By centering farmers as stewards, this program can be instrumental in transforming Punjab's depletion trajectory into a model for climate-adaptive agriculture nationwide, aligning with SDGs on zero hunger and climate action (Sharma et al., 2026).

Keywords: Groundwater depletion, climate smart agriculture, sustainable development, Indian agriculture

Introduction

India's agriculture heavily depends on groundwater, with over 60% of irrigation drawing from it, leading to rapid depletion in states like Punjab and Haryana. Groundwater depletion represents a silent yet severe environmental and economic crisis. India is the world's largest consumer of groundwater, with more than 60% of irrigation dependent on it, while agriculture alone consumes nearly 80–90% of extracted groundwater (Central Ground Water

Board, 2023; Food and Agriculture Organization, 2022). Over-exploitation of aquifers threatens food security, urban sustainability, and rural livelihoods (World Bank, 2010). Despite its magnitude, the crisis receives limited public attention, allowing long-term damage to accumulate.

Groundwater depletion contributes significantly to climate change through multiple interlinked pathways. First, declining water tables necessitate deeper groundwater pumping, which requires

substantially higher energy inputs—often derived from fossil fuels—thereby increasing carbon dioxide emissions and reinforcing carbon-intensive irrigation systems (Food and Agriculture Organization, 2022; Shah, 2009). In water-stressed regions, crops demand greater irrigation and fertilizer application, leading to higher emissions of methane (CH₄) and nitrous oxide (N₂O), both potent greenhouse gases that accelerate global warming (Intergovernmental Panel on Climate Change, 2022).

Second, groundwater depletion can disrupt regional hydrological cycles and land-atmosphere interactions. Reduced soil moisture and declining water tables weaken evapotranspiration processes that help regulate rainfall, potentially destabilizing monsoon systems and making seasonal precipitation more erratic (Rodell et al., 2009; IPCC, 2022). Third, excessive groundwater extraction contributes to land degradation and carbon loss. Drying soils, declining wetlands, and ecosystem stress can release previously stored soil carbon into the atmosphere, transforming terrestrial systems from carbon sinks into carbon sources. Intensive irrigation practices may also degrade soil structure and reduce long-term agricultural productivity (FAO, 2022; Sharma, G, 2025; N. Rajput, 2024).

The dominant rice-wheat cropping system further exacerbates these impacts. Rice cultivation typically requires approximately 3,000–5,000 litres of water per kilogram of grain, resulting in heavy reliance on irrigation. Continuous cultivation of water-intensive crops increases electricity consumption for pumping, thereby elevating greenhouse gas emissions and reinforcing the climate-water-energy nexus (FAO, 2022; Shah, 2009). The dominant rice-wheat cropping system in states such as Punjab and Haryana intensifies the problem. Water-intensive cultivation practices prevent aquifers from replenishing naturally, leading to falling water tables and increased vulnerability to climate variability (Rodell et al., 2009; Shah, 2009). As water extraction in these states becomes deeper, energy use rises, further contributing to greenhouse gas emissions and climate change (FAO, 2022; Chopra, D, 2024). Thus, groundwater depletion is not merely a water issue but a complex climate-development

challenge requiring capacity building, policy reform, and behavioural change (World Bank, 2010; Shah, 2009). This study therefore emphasizes on empowering Punjab farmers through targeted training in sustainable practices to build resilience and ensure long-term food security.

1. Climate Smart Agriculture: Mitigating Impacts, Adapting to Change, and Enhancing Productivity in Indian Groundwater Contexts

Climate Smart Agriculture (CSA) represents a transformative approach to farming that simultaneously addresses three critical pillars: mitigating greenhouse gas emissions, adapting to climate variability, and enhancing productivity to ensure food security (Mehta S, 2025). In India, where agriculture consumes 80-90% of groundwater resources and faces acute depletion in states like Punjab, CSA offers practical solutions tailored to water-scarce environments. By integrating low-water cropping systems, precision irrigation, and community-based resource management, CSA transforms groundwater-dependent agriculture into a resilient model that reduces environmental harm while boosting farmer incomes.

2.1 Mitigation Through Resource-Efficient Practices

CSA significantly cuts emissions from agriculture's water-energy nexus. Direct Seeded Rice (DSR) reduces irrigation needs by 15-25% compared to traditional flooded paddy, while slashing methane emissions by 30-40% through intermittent drying. Micro-irrigation systems like drip and sprinkler deliver 30-50% water savings, minimizing energy-intensive pumping that relies on fossil fuel-generated electricity. Crop diversification to climate-resilient millets—requiring just 300-500 mm rainfall versus rice's 3,000-5,000 liters per kg—lowers both groundwater extraction and the carbon footprint of irrigation (ibid).

Managed Aquifer Recharge (MAR) further enhances mitigation by capturing monsoon runoff through check dams and percolation tanks, reducing flood risks while replenishing aquifers. Solar-powered pumps with grid integration prevent over-pumping by enabling farmers to sell surplus electricity, replacing diesel and coal-based power.

These practices align with India's Nationally Determined Contributions under the Paris Agreement, positioning agriculture as a carbon sink rather than a source.

2.2 *Adaptation to Climate Variability*

India's erratic monsoons and rising temperatures demand adaptive strategies that CSA delivers through diversified systems. Drought-tolerant crops like pearl millet and pulses maintain yields under reduced rainfall, while short-duration paddy varieties allow time for aquifer recovery between seasons. Community water budgeting, as demonstrated in Maharashtra's watershed projects, empowers villages to monitor groundwater bi-monthly and allocate resources for crops, livestock, and domestic needs.

Precision technologies enhance adaptation by matching water inputs to real-time soil moisture and weather data. Hyper-local agro-met advisories guide planting decisions, reducing crop failures by 20-30% in rainfed areas. Soil conservation measures—water absorption trenches, contour bunding—stabilize slopes and improve water retention, critical as projections show 6-14% increased precipitation variability by 2080. These interventions build systemic resilience, protecting Punjab's 78% over-exploited blocks from collapse (The Energy and resource Institute, 2019).

2.3 *Productivity Enhancement and Economic Viability*

CSA drives productivity gains without compromising sustainability. Micro-irrigation boosts yield by 20-30% through precise nutrient delivery, while DSR cuts labor costs by 30% and cultivation expenses. Diversification to high-value basmati or maize generates premium prices—Haryana pays Rs. 7,000/acre incentives—while maintaining food security through balanced cropping. Solar pumps reduce operational costs by 50-70%, with grid sales adding income streams that exceed diesel expenses.

In eastern India, untapped shallow aquifers offer CSA opportunities for a second Green Revolution. Electrification paired with metering prevents western-style depletion, while solar drip systems

minimize emissions. NICRA demonstrations across Bihar, Maharashtra, and Rajasthan confirm 25-30% global warming potential reductions alongside higher outputs. Farmer-managed systems like APFAMGS show self-regulation sustains yields without aquifer loss.

Therefore, Climate Smart Agriculture represents India's pathway from groundwater crisis to climate-resilient prosperity. By mitigating emissions through efficient practices, adapting via diversified systems, and enhancing productivity with precision tools, CSA can be instrumental in addressing Punjab's depletion trajectory while scaling nationally. With 1.5 million farmers at stake, integrating CSA into state policies—stronger enforcement, diversified procurement, renewable irrigation, can ensure that agriculture contributes to SDGs on zero hunger, climate action, and sustainable water management.

2. **State-Led Interventions for Groundwater Conservation in India**

Indian states serve as primary custodians of groundwater resources under India's federal water governance framework, implementing regulatory, infrastructural, and incentive-based strategies to combat depletion. States enforce demand-side restrictions through Groundwater Acts and ordinances. Punjab's Preservation of Sub-Soil Water Act (2009) mandates paddy transplanting after June 10, curbing pre-monsoon pumping that previously drained aquifers during peak summer demand. Haryana mirrors this with June 5 deadlines, reducing extraction by 10-15% while maintaining yields through short-duration varieties. States like Gujarat, Maharashtra, Uttar Pradesh, and Andhra Pradesh regulate borewell permits, depth limits, and "no new wells" zones in over-exploited blocks, though monitoring gaps persist.

Several regions in India have implemented participatory groundwater management initiatives that rely on community capacity building rather than purely regulatory approaches. Evidence from multiple states indicates that sustainable water savings can be achieved when local institutions are empowered through training, information sharing, infrastructure support, and collective decision-

making. These initiatives provide valuable models for replication in other groundwater-stressed areas.

The *Atal Bhujal Yojana (ABY)* represents a large-scale national effort to strengthen decentralized groundwater governance. Implemented across thousands of villages in seven states, the programme emphasizes the preparation of Village Water Security Plans by Gram Panchayats (Ministry of Jal Shakti, 2023). Through extensive training and awareness campaigns, local communities are encouraged to adopt crop diversification, micro-irrigation technologies, and groundwater recharge measures. The construction of numerous recharge structures has enhanced rainwater infiltration, while community monitoring has helped moderate extraction rates. Evaluations suggest measurable improvements in groundwater conditions in several administrative units, demonstrating the effectiveness of demand-side management supported by local participation (ibid).

Another important initiative is the MARVI (Managing Aquifer Recharge through Village-level Intervention) project, implemented by the International Water Management Institute and partner organizations in western India. This project focuses on participatory aquifer management through village cooperatives equipped with monitoring tools such as piezometers. Regular groundwater measurements are shared with farmers, enabling informed decisions regarding irrigation practices. Recharge interventions, including check dams and percolation structures, complement these efforts. Participating farmers have adopted water-efficient irrigation techniques and coordinated pumping schedules, resulting in reduced water use without compromising agricultural productivity (International Water Management Institute [IWMI], 2019).

The Andhra Pradesh Farmer Managed Groundwater Systems (APFAMGS) programme provides an example of voluntary self-regulation by farmers. Operating in drought-prone districts, the initiative promotes collective monitoring of groundwater levels and transparent sharing of pumping data. Farmer groups determine sustainable extraction limits based on estimated recharge and encourage water-saving agricultural practices such as crop

planning adjustments and efficient irrigation methods (World Bank, 2010; Reddy et al., 2014). Studies report substantial reductions in groundwater extraction alongside stable crop yields, indicating that social norms and shared accountability can effectively regulate resource use.

Overall, these programmes demonstrate that community ownership, transparent information systems, and continuous capacity building are critical to sustainable groundwater management. Their success highlights the limitations of top-down regulatory approaches and underscores the importance of participatory institutions in addressing complex water challenges. The experiences from these states offer practical lessons for designing scalable interventions in other regions facing severe groundwater depletion like Punjab.

Even though these strategies are in place, not much saving has been ensured especially in the state of Punjab where groundwater depletion has become a steady agricultural crisis. The Central Ground Water Authority (CGWA) regularly notifies critical areas, and state-level enforcement drives compliance through electricity disconnection penalties or nursery destruction for violations. However, Punjab's flat tariffs encourage deeper pumping that worsens the problem of ground water depletion across the state. Also, an incentive System of 'Diversification payments' to counter rice-wheat dominance has also been introduced. Haryana offers Rs. 7,000/acre for 16 alternatives (cotton, maize, pulses) whereas in Punjab only a small incentive of Rs. 1,000-1,500/acre for basmati/maize is extended to farmers for crop diversification.

3. Capacity Building Program for Sustainable Groundwater Management in Punjab

Punjab faces one of the most severe groundwater crises in India due to decades of water-intensive agriculture, particularly the rice-wheat cropping system. Declining water tables threaten long-term agricultural productivity, rural livelihoods, and food security. Addressing this challenge requires more than technological fixes or regulatory measures; it demands systematic capacity building across multiple stakeholders—from farmers and village

institutions to government officials and implementing agencies.

Capacity building enables stakeholders to understand groundwater dynamics, adopt climate-smart agricultural practices, and participate in collective resource management. Evidence from participatory groundwater programmes in India demonstrates that informed communities are more likely to reduce over-extraction and adopt sustainable practices (World Bank, 2010; Reddy et al., 2014). Therefore, a comprehensive training-based intervention tailored to Punjab's agro-ecological conditions is essential for transitioning toward climate-resilient agriculture.

The proposed program as shown in Figure 1 adopts a multi-level approach aimed at strengthening the capacities of farmers, community institutions, extension personnel, and policymakers to promote sustainable groundwater management. Recognizing that groundwater depletion is both a technical and socio-institutional problem, the program integrates technical training, behavioural change interventions, and institutional strengthening. The overarching goal is to foster participatory groundwater governance that enables stakeholders to make informed decisions regarding water use while enhancing climate resilience in agriculture.

4.1 Awareness and Groundwater Hydrology Training

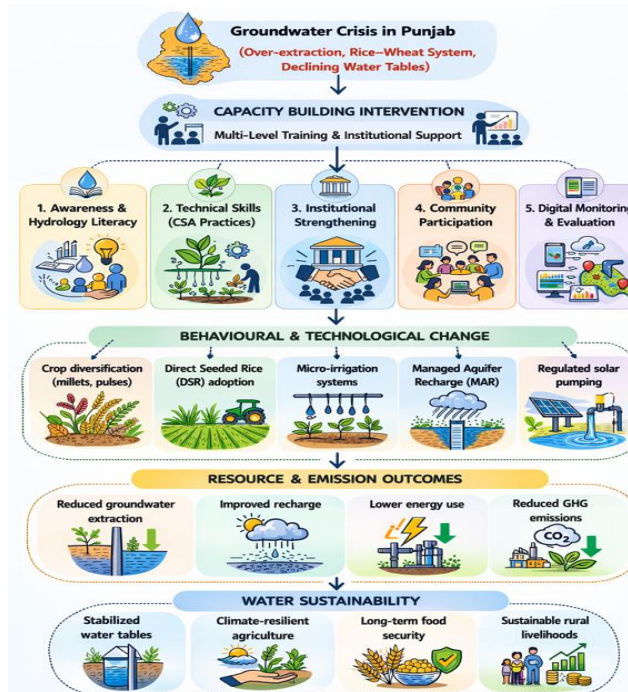
The first component focuses on developing foundational knowledge of groundwater systems, aquifer dynamics, and sustainable extraction limits. In regions such as Punjab, where groundwater decline is largely invisible until severe depletion occurs, improving hydrological literacy among local stakeholders is essential. The key target groups for

this intervention would be: Farmers, Gram Panchayats, and village-level water committees. Training sessions will cover basic groundwater hydrology, aquifer behaviour, and the consequences of excessive extraction. Participatory monitoring methods will be introduced, including regular measurement of water levels in wells and estimation of village-level water balance. Awareness campaigns will communicate the long-term ecological and economic risks associated with unsustainable pumping (Reddy et al., 2014). This component is expected to enhance understanding of groundwater depletion, foster community ownership of water resources, and reduce unsustainable pumping through informed decision-making.

4.2 Technical Skills Development

The second component emphasizes the practical adoption of water-efficient and climate-smart agricultural technologies. Given Punjab's heavy reliance on water-intensive paddy cultivation, technical interventions that reduce irrigation demand are critical. Target Groups here would include: Farmers, agricultural extension workers, and technical personnel. Hands-on demonstrations will be conducted for Direct Seeded Rice (DSR), which reduces water use and methane emissions compared to traditional flooded paddy cultivation. Training will also cover micro-irrigation systems such as drip and sprinkler technologies, promotion of low-water crops (particularly millets and pulses), and implementation of Managed Aquifer Recharge (MAR) structures. The adoption of these practices is expected to significantly reduce irrigation water demand, lower greenhouse gas emissions from agriculture, and improve productivity per unit of water used.

Figure 1: Proposed capacity building framework to address ground water depletion problem of Punjab



Source: Authors own compilation

4.3 Policy and Institutional Training

Sustainable groundwater management cannot be achieved without supportive governance frameworks and institutional coordination. This component seeks to strengthen the capacity of policymakers and implementing agencies to design and operationalize water-conservation policies. Under this the target group would include: Government officials, non-governmental organizations, and leaders of farmer cooperatives. Training will focus on incentive mechanisms for crop diversification, awareness of relevant national schemes such as the Pradhan Mantri Krishi Sinchayee Yojana (PMKSY) and the Atal Bhujal Yojana, and capacity building for regulating solar-powered irrigation systems, including grid integration. The program will also support the formation and strengthening of farmer cooperatives and water user associations to facilitate collective resource management. Institutional support is widely recognized as a critical factor in scaling local initiatives and ensuring long-term sustainability (World Bank, 2010). Expected outcomes include strengthened governance mechanisms, improved

inter-agency coordination, and incentive structures aligned with groundwater conservation objectives.

4.4 Digital Monitoring and Evaluation Systems

Continuous monitoring and evaluation are essential for ensuring accountability, transparency, and adaptive management. This component integrates digital tools and participatory mechanisms to track program performance and groundwater trends across all stakeholders, including farmers, community institutions, and government agencies. Monitoring systems will include app-based tracking of groundwater levels, irrigation practices, and cropping patterns. Annual performance audits will assess progress toward program objectives, while data-driven crop planning will guide adaptive management strategies. Feedback mechanisms will allow stakeholders to refine interventions based on observed outcomes. This component is expected to support evidence-based decision-making, adaptive cropping strategies, and increased resilience to groundwater depletion.

4. Phased Implementation Strategy

The successful implementation of a capacity building program for sustainable groundwater

management in Punjab requires a carefully structured, phased approach. Given the scale of groundwater depletion and the socio-economic dependence on water-intensive agriculture, interventions must be introduced gradually to ensure acceptance, effectiveness, and long-term sustainability. A phased strategy allows for systematic planning, pilot testing, scaling, and institutionalization while minimizing disruption to agricultural livelihoods.

The first phase, spanning the initial three months, focuses on preparation and baseline assessment. This stage establishes the institutional and informational foundation necessary for program implementation. Priority districts experiencing severe groundwater decline are identified using

hydrological data and administrative records. Comprehensive baseline surveys are conducted to assess groundwater levels, cropping patterns, irrigation practices, socio-economic conditions, and farmer perceptions. Stakeholder consultations involving government agencies, local authorities, research institutions, and community representatives help build consensus and ensure that the program design reflects local realities. During this phase, training curricula and communication materials are developed in collaboration with technical experts and partner organizations. Establishing a baseline is critical, as it provides reference points against which future progress can be measured and enables evidence-based evaluation of program outcomes.

Figure 2: Phased Implementation Strategy for capacity building programs across Punjab



Source: Authors own compilation

The second phase, covering months four to twelve, involves intensive capacity building at the grassroots level. Training programs are delivered to farmers, village committees, and extension personnel through workshops, field demonstrations, and farmer field schools. Emphasis is placed on enhancing awareness of groundwater depletion, promoting climate-smart agricultural practices, and introducing water-efficient technologies such as Direct Seeded Rice, micro-irrigation systems, and crop diversification toward low-water crops like

millet and pulses. Pilot demonstration plots are established to showcase the agronomic and economic feasibility of alternative practices. Extension workers receive specialized training to provide continuous technical support, ensuring that knowledge transfer translates into practical adoption. Early adopters play a crucial role during this phase by demonstrating the benefits of sustainable practices to neighbouring farmers, thereby facilitating diffusion of innovations within rural communities.

The third phase, extending from months thirteen to twenty-four, focuses on scaling up successful interventions and strengthening participatory governance mechanisms. Practices validated during the pilot stage are expanded to additional villages and districts. Training programs are extended to government officials, cooperative leaders, and local institutions to ensure administrative support and policy alignment. Village-level water user associations are established or strengthened to promote collective decision-making regarding groundwater extraction and crop planning. Digital tools and mobile applications are deployed to monitor groundwater levels, irrigation patterns, and program performance in real time. Infrastructure interventions, such as the construction of recharge structures and the promotion of regulated solar pumping, are also implemented at scale. This phase aims to achieve measurable reductions in groundwater extraction and significant shifts toward less water-intensive cropping systems.

The final phase, spanning months twenty-five to thirty-six, emphasizes evaluation, policy integration, and sustainability. Independent impact assessments are conducted to determine the effectiveness of the program in improving groundwater conditions, agricultural productivity, and farmer livelihoods. Findings from these evaluations inform policy recommendations for scaling the program across the state or integrating it into national initiatives such as participatory groundwater management schemes. Efforts are made to institutionalize successful practices by embedding them within existing governance structures, extension services, and community organizations. Capacity building during earlier phases ensures that local institutions are capable of continuing program activities without external support. Establishing self-sustaining mechanisms—such as community monitoring systems, cooperative management structures, and incentive-based policies—helps secure long-term water sustainability.

Table 1: Proposed Phased Implementation of capacity building programs in Punjab

Phase & Timeline	Key Objectives	Major Activities	Punjab-Specific Focus Areas & Statistics	Lead & Supporting Agencies	Monitoring Indicators / Outputs
Phase 1: Preparation & Baseline (Months 1–3)	Establish institutional framework and assess groundwater status	<ul style="list-style-type: none"> Stakeholder consultations Baseline surveys of groundwater levels Identification of priority districts Curriculum development Partnership agreement 	<ul style="list-style-type: none"> Punjab extracts ~165–170% of its annual groundwater recharge (over-exploited category) Over 75% administrative blocks classified as “over-exploited” Focus on central districts (e.g., Sangrur, Moga, Barnala, Patiala) with steep water table decline 	Ministry of Jal Shakti, CGWB, Punjab Water Resources Dept., State Agriculture Dept., Universities	<ul style="list-style-type: none"> Baseline groundwater database created Priority villages identified Training modules finalized
Phase 2: Core Training & Pilot Implementation (Months 4–12)	Build awareness and technical capacity at grassroots level	<ul style="list-style-type: none"> Farmer workshops on groundwater hydrology Demonstrations of DSR, drip irrigation, MAR Pilot plots for millet diversification Formation of village water committees Training extension workers 	<ul style="list-style-type: none"> Agriculture uses ~80–85% of Punjab’s water resources Rice–wheat system dominates ~80% of cultivated area High electricity subsidy encourages excessive pumping 	State Agriculture Dept., KVKs, NGOs, PMKSY Mission Units, Farmer Producer Organizations	<ul style="list-style-type: none"> Number of farmers trained (target: 10,000+) Demonstration plots established Initial adoption of CSA practices Formation of water user groups



Phase 3: Scale-Up & Participatory Governance (Months 13–24)	Expand adoption and institutionalize community management	<ul style="list-style-type: none"> • Training of officials and cooperative leaders • Establish village-level groundwater user associations • Deployment of digital monitoring apps • Construction of recharge structures • Incentivized crop diversification programs 	<ul style="list-style-type: none"> • Water table declining ~0.5–1.0 meter per year in many districts • Tube well density among highest in India • Heavy dependence on free/subsidized electricity 	Ministry of Agriculture, State Govt., CGWB, DISCOMs, NGOs, Research Institutes	<ul style="list-style-type: none"> • Increase in area under low-water crops (target: 20–30%) • Number of recharge structures built • Reduction in pumping intensity • Operational water cooperatives
Phase 4: Evaluation, Policy Integration & Sustainability (Months 25–36)	Ensure long-term continuity and policy mainstreaming	<ul style="list-style-type: none"> • Impact assessment and independent evaluation • Refinement of training modules • Policy advocacy for scaling • Integration with national schemes (e.g., Atal Bhujal Yojana) • Establish self-sustaining local institutions 	<ul style="list-style-type: none"> • Long-term goal: stabilize groundwater decline and reduce dependence on paddy cultivation • Align with national food security and climate goals 	Central & State Governments, Policy Think Tanks, World Bank, FAO, Academic Institutions	<ul style="list-style-type: none"> • Measurable improvement in groundwater trends • Institutionalization within state programs • Sustained adoption of CSA practices • Replicable model for other states

Source: Authors own compilation

The phased implementation strategy provides a structured pathway for transitioning from awareness to sustained action. By beginning with evidence-based planning, advancing through intensive training and pilot interventions, expanding through institutional strengthening, and concluding with evaluation and mainstreaming, the approach addresses both technical and socio-political dimensions of groundwater management. Such a gradual and participatory process is essential for achieving durable behavioural change, ensuring farmer acceptance, and ultimately restoring groundwater balance in Punjab while safeguarding agricultural productivity and food security.

5. Conclusion

Punjab’s groundwater crisis represents a critical environmental and developmental challenge for Indian agriculture. Prolonged dependence on the water-intensive rice–wheat cropping system, coupled with energy subsidies that encourage excessive pumping, has led to severe aquifer depletion across the state. With a majority of administrative blocks classified as over-exploited and water tables continuing to decline, the sustainability of Punjab’s agricultural economy—and India’s food security—faces serious risk. As this

study demonstrates, groundwater depletion is not merely a water management issue but a complex climate–development problem linked to energy use, cropping patterns, institutional frameworks, and farmer behaviour.

The analysis highlights those regulatory measures and technological interventions alone cannot reverse depletion trends. While policies such as transplanting restrictions and diversification incentives have produced limited improvements, they have not addressed the underlying drivers of unsustainable extraction. Evidence from participatory groundwater initiatives in other Indian states shows that community-based capacity building can deliver more durable outcomes by fostering collective responsibility and informed decision-making. Accordingly, this study proposes a comprehensive capacity building framework tailored to Punjab. The program emphasizes multi-level training for farmers, community institutions, extension workers, and policymakers. Core strategies include improving hydrological literacy, promoting climate-smart agricultural practices such as Direct Seeded Rice and micro-irrigation, encouraging crop diversification toward low-water crops, implementing managed aquifer recharge, and regulating solar-powered irrigation. By combining

technical knowledge with behavioural change and institutional strengthening, the framework seeks to transform farmers into active stewards of groundwater resources.

The phased implementation strategy enhances feasibility by allowing gradual adoption—from baseline assessment to pilot interventions, scaling, and institutionalization. If effectively implemented, the program can reduce groundwater extraction, improve aquifer recharge, enhance climate resilience, and sustain agricultural productivity. Ultimately, farmer-led capacity building offers the most viable pathway for restoring groundwater sustainability in Punjab while providing a replicable model for climate-adaptive agriculture in other water-stressed regions.

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