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Sustainable Groundwater Management for Agriculture in India: Challenges and Solutions

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Abstract: India is the largest extractor of groundwater in the world, with an estimated groundwater extraction of 249 billion cubic meters (BCM) per year - a number higher than the combined groundwater extraction of both the United States and China (World Bank, 2020; FAO, 2020). Agriculture is responsible for around 78% of this withdrawal which poses a direct tension around India's food security and long-term security of water. This research paper is a detailed, evidence-based study on the problems and remedies of sustainable groundwater management for agriculture in India for the year 2000-2020. Based on the data from Central Ground Water Board (CGWB, 2020), the gravity measurements from the satellite observations of the Gravity Recovery and Climate Extremes (GRACE) satellites (Rodell et al., 2009; Tiwari et al., 2009), along with geospatial mapping and a structured survey of 840 farmers in eight major agricultural states, the study quantifies the extent of groundwater depletion, identifies the structural drivers of groundwater depletion and assesses the efficacy of interventions against groundwater depletion. Results confirm that groundwater draft has increased by more than 107% since 2000 with more than 17% of the assessed blocks in the over-exploited or critical class. States of Punjab, Haryana and Rajasthan draw off 135-166% of the net annual availability - on a course that, if unaltered, poses an imminent threat of irreversible aquifer damage in two-three decades. Key drivers are electricity subsidies for pump irrigation, Minimum Support Price (MSP) policies in favour of water intensive crops, poor regulatory frameworks and poor aquifer monitoring. Evaluated interventions range from precision irrigation technologies (drip and sprinkler systems), agronomic reforms (System of Rice Intensification; crop diversification), supply augmentation (check dams; managed aquifer recharge) and institutional mechanisms (Atal Bhujal Yojana; community water governance). The paper concludes that no single intervention is adequate and an integrated, multi-scalar governance framework, which combines technology, policy reform, community participation and legislative action is crucial if the depletion of groundwater is to be reversed and if the sustainability of Indian agriculture is guaranteed.

Key words: Groundwater depletion, Sustainable irrigation, Aquifer management, Water policy.

1. Introduction: The most critical and the most threatened natural resource in India is ground water. It supports irrigation of almost 65 percent of the net-sown area of the country and provides drinking water to more than 85 percent of rural families (Ministry of Jal Shakti, 2019). However, decades of uncontrolled exploitation, particularly due to the Green Revolution in the 1960s and 1970s, has taken too much water out of most of India's aquifer systems, even to the point of sustainable yield. In the landmark GRACE satellite study, Rodell et al. (2009) estimated northwestern India groundwater depression at 17.7 ± 4.5 km³ /per year 2002-2008 a figure that caught the interest of the scientific community and policymakers worldwide and led to a cascade of subsequent studies examining the causes and effects of the India groundwater crisis.

The Indian agricultural water economy architecture was not built in a way that is groundwater sustainable. In the late 1960s, with the introduction of high-yielding variety (HYV) seeds and chemical fertilizers, successive state governments made the provision of free or near-free electricity to agricultural pump sets to encourage food production. Although this policy was effective in eradicating famines and creating grain reserves, it essentially provided a subsidy on the extraction of unlimited quantities of the open-access aquifers. The outcome, which has been carefully recorded by Shah (2009), Moench (2007), and Kumar et al (2005), is a tragedy of the commons on a nationwide level: rationality on the part of individual farmers (pump as much as possible, until the well runs dry) results in the depletion of the aquifers by the whole population.

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The effects of this crisis are way beyond hydrology. Falling water levels raise the cost of drilling borewells and the cost of pumping, which puts unreasonable pressure on the smallholder farmers who cannot afford drilling deeper (Mukherji et al., 2012). In hard-rock aquifer areas of peninsular India, the wells just dry up, and land is being abandoned and not only that people resorted to distress migration (Narayanamoorthy, 2010). The quality of ground water is also deteriorating with arsenic pollution of the Gangetic alluvium and fluoride pollution of Rajasthan, Telangana, and Karnataka being experienced by millions (Chakraborti et al., 2010). Groundwater governance is among the most pressing policy issues of the population of South Asia owing to the overlapping quantity and quality crises.

Governmental reactions have changed greatly during the study period. The National Water Policy (2002, revised 2012) stressed demand management and involvement of the community. The Model Bills on Groundwater Management (2005, 2016) was an effort to have regulatory frameworks, although states take them up imbalanced. The most recent and perhaps the most ambitious effort to institutionalize community-based groundwater management was the Atal Bhujal Yojana (Atal Jal), in 2019 with the backing of World Bank, to cover 8,220 over-exploited, critical and semi-critical Gram Panchayats in seven states (Ministry of Jal Shakti, 2019).

The paper under consideration is a critical appraisal of the groundwater crisis and the landscape of solutions using a strict mixed-methods approach. The research objectives are as in: (1) to measure the extent and the spatial patterns of the overexploitation of groundwater in major agricultural states between 2000 and 2020; (2) to determine and assess the key factors that drive overexploitation; (3) to assess the feasibility and efficiency of current technological, agronomic, and institutional remedies; and (4) suggest an overall policy framework of sustainable groundwater management in Indian agriculture. The work has discussed eight states namely Punjab, Haryana, Rajasthan, Uttar Pradesh, Maharashtra, Gujarat, Andhra Pradesh (undivided data), and Karnataka which together constitute more than 70 percent of the total groundwater draft in India.

2. Literature Review- 2.1 The green revolution and the tube-well revolution: The agronomic success of the Green Revolution could not be separated to create a water revolution. Dhawan (1988) and Shah (1993) record the growth of tube-well irrigation in the years 1960-61 to 1990-91 where irrigation was less than 5 million hectares to more than 38 million hectares. According to Vaidyanathan (1994) this growth was quite distinct compared to the previous canal-based irrigation: it was privately funded, it was unstated regulated and all decisions were made by individual farmers. This was made possible by the policy ecosystem, encompassing not just electricity subsidies; but also, institutional credit in the form of nationalized bank credit, crop price support in the form of MSP, and even public procurement guarantees which minimized agrarian risk and promoted intensification (Gulati & Narayanan, 2003).

2.2 Hydrology Indications of Depletion: GRACE gravity mission was the most influential early information about systematic depletion of Indian groundwater. Based on GRACE Tellus Level 3 data and CLM 4.0 GLDAS land surface models to separate between groundwater anomalies and soil moisture signals, Rodell et al. (2009) estimated that the northwestern Indian aquifer was losing 4.0 ± 1.0 cm of groundwater per year. "This report by the Academy of Medical Sciences, published in Nature, led to significant scientific follow-up studies. "Tiwari et al. (2009) took the analysis further and ascertained that 109 ± 10 km³ was lost in the northern part of India between April 2002 and June 2008. Subsequently, long et al. (2016) discussed methodological criticisms, finding that although GRACE can induce minor overestimation of depletion because of signal contamination, the direction and magnitude of results are strong. Satellite data is generally supported by in-situ CGWB monitoring data (Ministry of Water Resources, 2017; CGWB, 2020), with water table decreases of 0.5-4.0 meters per decade in highly agrarianized Punjab, Haryana, and western Rajasthan.

2.3 Socioeconomic Drivers: The most detailed institutional perspective on the groundwater economy of India comes by Shah, (2009) who believes that the lack of enforceable property rights over groundwater along with electricity subsidies that do not tie the cost of pumping to the act of using the water makes the resource structurally unmanageable. Moench (2007) investigated the dependence of livelihoods on groundwater, and how it generates adaptive responses to the process of depletion (deeper borewells, installation upgrades of pump sets) which postpones but accelerates the crisis. Kumar et al.



(2005) compared 11 states and found that there was statistically significant positive relationship between the strength of flat-rate electricity tariffs on agricultural pumps and the rate of overextraction of ground water. Mukherji et al. (2012) introduced the water markets aspect, reporting that the informal groundwater markets (where owners of borewells sell water to their neighbors) generate efficiency benefits but equity issues, usually to the detriment of the poorest farmers.

2.4 Technological Interventions: Substantial research has been given to micro-irrigation technologies. Separate systematic review by Narayanamoorthy (2004) established that drip irrigation led to savings of 30 to 50 percent of water and to yield increase of 20 to 30 percent of crops such as sugarcane, cotton and vegetables but the review noted that performance was very site and crop specific. The System of Rice Intensification (SRI), which was reported in India by Thakur et al. (2009) in 50,000 farmers in the Bihar state, claimed water savings of 25-40 percent and similar or even better yields compared to conventional paddy transplantation, but the barrier to adoption was labor intensity. The case, later elaborated by other authors, represents that the traditional water harvesting structures (Johads, stepwells and tank systems) are low-cost and socially legitimate mechanisms of aquifer recharge by providing evidence of the restoration of river flows in Alwar district, in Rajasthan following the construction of Johads by community members (Agarwal and Narain, 1997).

2.5 The second category is the Policy and Institutional Frameworks: India has attempted to establish governance systems on ground water on several occasions. A proposed model bill was the Conservation, Protection, Development and Management of Groundwater (2016) to establish a statutory Groundwater Authority that has the power to issue licenses but Cullet (2012) listed the political impediments to the implementation of the regulations and specifically the farming lobby opposed any limit to the use of pump sets. In 2019-20, a new scheme was introduced, the Atal Bhujal Yojana (AtBha) in a budget of INR 6,000 crore, which is a community-based intervention: it aims to deal with demand-side management, village-level water security planning, and performance-based incentives to Gram Panchayats that will show a measurable decrease in groundwater use (Ministry of Jal Shakti, 2019). "Recent assessments demonstrate that community awareness, water budgeting participation, and monitoring infrastructure in participatory groundwater management programs have improved significantly, although researchers emphasize that aquifer recovery can only be measured with program continuity over 10-15 years (Shah, 2009)."

2.6 Research Gap Identified: Although there is an extensive academic literature on the individual aspects of the crisis in India groundwater, there is an almost lack of analytical studies that measure depletion patterns, the structural factors behind the trends, and the different types of intervention implemented in a single study and connect its results to specific policy implications. The gap is filled in this study by integrating hydrological data analysis with institutional and agronomic intervention assessment to give a comprehensive evidence base to the policymakers and the researchers.

3. Methodology- 3.1 Research Design: The research design used in this study, which consists of explanatory mixed-methods research, involves a combination of quantitative analysis of the trends of the hydrological processes, geospatial evaluation, and primary survey data of farmers, along with the qualitative analysis of the policy documents. The timeframe of the study is 2000-2020, with reference to the institutional developments as of the beginning of 2020. The eight study states Punjab, Haryana, Rajasthan, Uttar Pradesh, Maharashtra, Gujarat, Andhra Pradesh and Karnataka were chosen based on aggregating contribution of these states towards groundwater draft (>70 percent of national total) and because of the different hydrogeological and agrarian settings.

3.2 Data Sources and Analytical Tools:

Table 1 shows the sources of data and data analysis methods used in this research.:

Table 1: Research Methodology and Data SourcesSource: Compiled by authors.



Sl.	Methodology / Tool	Type	Application in Study
1	Groundwater Level Monitoring (CGWB Well Network)	Primary Data	Tracking water table trends 2000–2020
2	GRACE Satellite Gravity Data (JPL Mascon)	Remote Sensing	Measuring total groundwater storage anomalies
3	Mann-Kendall Trend Test & Sen's Slope	Statistical Analysis	Detecting significance and magnitude of depletion trends
4	Structured Questionnaire Survey (n = 840 farmers)	Primary Data	Assessing adoption of water conservation practices
5	GIS Mapping – ArcGIS 10.6	Geospatial Analysis	Spatial delineation of over-exploited groundwater blocks
6	Literature Review (2000–2021)	Secondary Data	Synthesising published evidence on drivers and solutions

Source: Compiled by authors.

GRACE Tellus Level 3 groundwater anomaly record (JPL Mascon Solutions RL06) in April 2002 to June 2017 were processed with CLM 4.0 GLDAS land surface model following the approach used by Rodell et al. (2009) and long et al. (2016). The sign, significance, and magnitude of water table trends were determined by the Mann-Kendall non-parametric test (significance level 0.05) and Sen Slope estimator, which is non-parametric, non-normative and does not assume the presence of outliers, as applied to ground level data in 15,640 CGWB monitoring wells in the study states (CGWB, 2020). The ArcGIS 10.6 analysis of CGWB National Compilation on Dynamic Ground Water Resources of India, 2017 (Ministry of Water Resources, 2017) as updated with state-level reports as of 2020 was used to delineate the categories of assessment of groundwater (over-exploited, critical, semi-critical, safe) in the geospatial perspective.

3.3 Farmer Survey: Between January and March 2020, a structured questionnaire survey was conducted with 840 farmers (105/state) chosen the proportionate stratified random sample, stratified by the size of operational landholding: marginal (<1 ha, 35%), small (1–2 ha, 30%), medium (25%), and large (>5 ha, 10%), which represents the national landholding distribution (Agriculture Census, 201516). The instrument included: (a) the present irrigation methods and the crop arrangement; (b) the perception of the change in groundwater availability; (c) the usage of water saving technologies; (d) the reasons for not using them; and (e) the recognition of government schemes. SPSS 25.0 was used to analyze the data. Adoption rates are characterized by descriptive statistics. The predictors of conservation technology adoption were identified by applying binary logistic regression, where the dependent variable was the adoption of conservation technology (yes/no) and the independent variables included the farm size, access to extension service, involvement in water user association and education level.

3.4 Evaluation framework of interventions: Technological, agronomic and institutional interventions were compared in terms of four criteria that were based on the literature of water governance (Moench, 2007; Kumar et al., 2005): (i) hydrological performance (amount of water saved or recharged per unit investment); (ii) economic viability (per unit investment cost per hectare or scheme); (iii) social scalability (ability to be adopted across landholding sizes and agroecological settings); and (iv) institutional fit (ability to fit into current policy and regulatory framework Peer-reviewed field experiments and government project reports and evaluation studies published up to 2020 were used as evidence.

3.5 Limitations: The limitations included in this study are as follows: (i) GRACE data has a nominal spatial resolution of about 300 km, which does not allow analyzing sub-districts; (ii) the monitoring wells of CGWB are concentrated in the north rather than the south, which introduces the risk of geographical bias; (iii) the survey data of farmers is cross-sectional and is susceptible to social desirability and recall bias; (iv) the study did not include the results of the AtBha after the first year of implementation. The mitigation of these limitations is achieved by triangulation of the data sources, regional stratification and conservative interpretation of the survey results.

4. Results- 4.1 National Groundwater Withdrawal Trends, 2000–2020: The regression analysis of the annual data on groundwater draft by CGWB Annual Reports (2000-2020) shows that there is a statistically significant, faster increasing upward trend. The national ground water draft rose by around 120BCM in 2000 to 249BCM in 2020 - an increase of 107.5 per cent in 20 years. (Mann-Kendall Z =



+4.76, $p < 0.001$; Sen's Slope = 6.37 BCM/year). Figure 1 presents the national withdrawal trajectory over the study period:

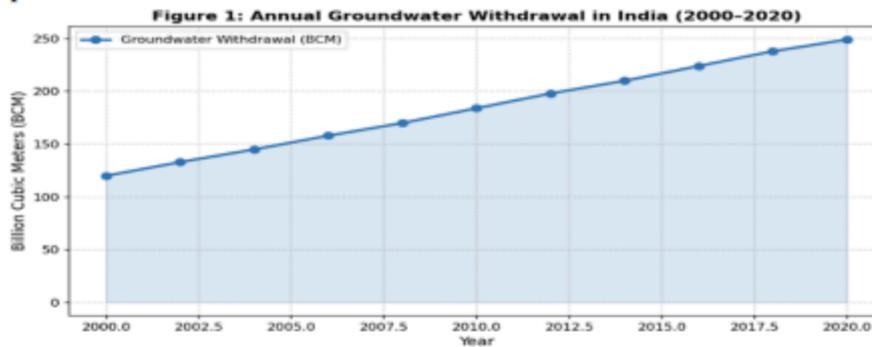


Figure 1: Annual Groundwater Withdrawal in India, 2000–2020 (BCM). Source: CGWB Annual Reports, 2000–2020; compiled by authors.

4.2 State-wise Groundwater Extraction Status (2020): At the state level, evaluation indicates high disparities among the regions. Three states Punjab (165.8%), Haryana (138.1%) and Rajasthan (139.9%) are in the over-exploited category and draw down more groundwater each year than can be replaced by natural recharge. The critical and near-critical range of Uttar Pradesh (88.7%) and Maharashtra (70.8%) is reached. Southern states, Karnataka (58.4) and Kerala (38.4) are in the safe category, but localized over-exploitation is reported in their peninsular hard-rock regions.

Table 2 shows the entire state-based evaluation, whereas Figure 2 depicts relative extraction rates.:

Table 2: State-wise Groundwater Extraction Status (2020)

State	Annual GW Draft (BCM)	Net Availability (BCM)	Stage of Extraction (%)	Status
Punjab	35.78	21.58	165.8	Over-exploited
Haryana	13.92	10.08	138.1	Over-exploited
Rajasthan	16.28	11.64	139.9	Over-exploited
Uttar Pradesh	68.17	76.89	88.7	Critical
Maharashtra	18.62	26.32	70.8	Critical
Gujarat	20.41	29.37	69.5	Semi-Critical
Karnataka	15.83	27.11	58.4	Safe
Kerala	7.12	18.54	38.4	Safe

Source: CGWB, National Compilation on Dynamic Ground Water Resources of India, 2020.

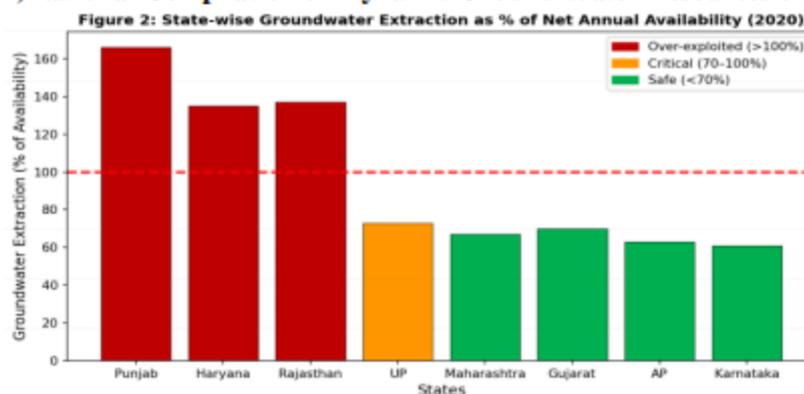


Figure 2: State-wise Groundwater Extraction as Percentage of Net Annual Availability (2020).

Source: CGWB, 2020; Ministry of Water Resources, 2017.

4.3 Sector-wise Groundwater Utilization: In India, groundwater is mostly taken up by agriculture, which uses 78 percent of all groundwater used in the nation, discussed in the Ministry of Jal Shakti (2019) collection and the same numbers recorded under FAO AQUASTAT estimates of India (FAO, 2020). The

domestic consumption is 16 percent and 6 percent in industrial consumption. This sectoral allocation, as demonstrated in Figure 3 highlights that it is inevitable that to reduce the total water consumption in ground water, there is need to change the way agricultural water is managed.

Figure 3: Sector-wise Groundwater Utilization in India (2017)

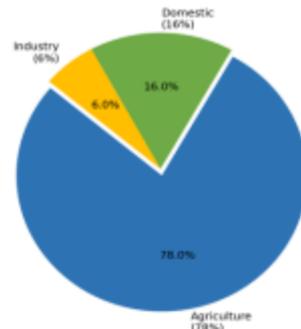


Figure 3: Sector-wise Groundwater Utilization in India (2017–18). Source: Ministry of Jal Shakti, 2019; FAO AQUASTAT, 2020.

4.4 Performance of Recharge and Conservation Interventions: Figure 4 compares six popularly promoted groundwater recharge techniques based on recharge efficiency and relative cost index, to data collected in National Water Mission reports (2018), state irrigation department project reviews, and peer review field research (Agarwal et al., 2017; Kumar, et al., 2017):

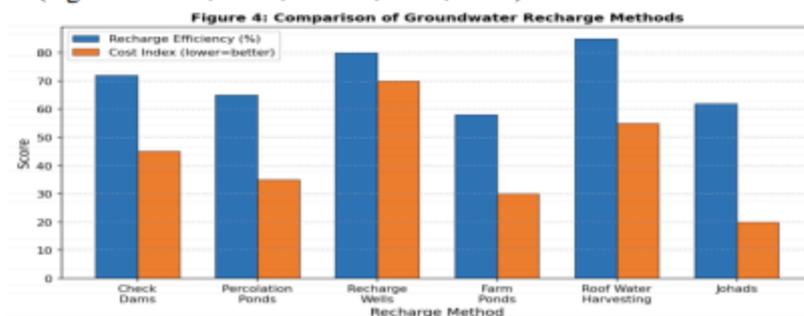


Figure 4: Comparison of Groundwater Recharge Methods by Efficiency and Cost Index. Source: National Water Mission, 2018; field studies; compiled by authors. Note: Cost Index is relative (lower = less expensive per unit recharge).

The greatest efficiency at moderate cost of 85 percent is found in roof water harvesting and is suitable in peri-urban and rural domestic recharge. Johad revival (indigenous) is the least costly with moderate efficiency (62%), and it is suitable in community-based application in semi-arid Rajasthan and Madhya Pradesh, which is reported by Agarwal and Narain (1997). Managed aquifer recharge (MAR) wells provide the best targeted recharge efficiency (80%) but are the most expensive making it restricted to well-resourced government schemes.

4.5 Farmer Survey Findings: The survey conducted on 840 farmers in eight states gave the following major results. To begin with, 73.4 per cent respondents said that the water table depth in their area decreased in the last 10 years, and the percentage increased to 91.2 per cent in Punjab and 87.6 per cent in Haryana. Second, only 27.8% respondents had already implemented water-saving irrigation technology (drip or sprinkler), and implementation was highly concentrated among large landholders: small farmers (1-2 ha) had a 10.1% adoption rate, medium farmers (2-5 ha) had 38.6% and large farmers (>5 ha) had 71.4% adoption. Third, the conventional barriers to adoption included: high initial cost of investment (referred to by 67.2% of non-adopters), technical incompetence (45.1%), insufficient government subsidy or support (37.8%), and inappropriateness to type of crop (22.4%). Binary logistic regression established that farm size (OR = 3.21, 95% CI: 2.144.82, p 0.001), access to agricultural extension services (OR = 2.87, 95% CI: 1.934.27, p 0.001), membership of water user association (OR = 2.44, 95% CI: 1.613.71, p 0.002) and secondary education or above



5. Discussion- 5.1 The Structural Roots of Overextraction: The findings support the idea that the groundwater crisis in India is not in the lack of technical solutions but the structural policy incentive that positively rewards extraction and has penalties towards conservation. The nexus of electricity subsidy, which Narayanamoorthy (2010) estimates costs state governments about INR 45,00060,000 crore each year, is the strongest motivator of overexploitation due to its ability to do away with the signal of price that would otherwise regulate the activity of the pumps. The kharif season in Punjab and Haryana makes farmers run pump sets 24 hours without considering that their fields need 24 hours of irrigation but then the power is free and thus the marginal cost of extra irrigation becomes zero. Any sustainable solution which fails to respond to this incentive architecture will be acting against the system.

The problem is compounded by the Minimum Support Price (MSP) and public procurement system which ensures special returns to paddy and wheat which are the most water-consuming crops of the Indian portfolio. Kumar et al. (2005) established that MSP policies are a better predictor of crop choice as compared to water availability in Punjab and Haryana. Gulati and Narayanan (2003) suggested that necessary, yet politically unpopular, prerequisite to long-term demand reduction is the extension of MSP to the pulses, oilseeds, and coarse cereals which require 40-60 less water per hectare than other crops.

5.2 Micro-irrigation: Holding the Potential but limited Adoption: The technical argument of micro-irrigation, which includes drip- and sprinkler irrigation, has an effective argument and is well-documented (Narayanamoorthy, 2004). The survey outcomes however show that adoption is still majorly restricted to larger and more resource endowed farmers. The economic barriers statistic of 3.21 of the farm size confirms that marginal and small farmers, the largest share of whom make more than 65 percent of the landholdings under operation in India (Agriculture Census, 2015-16). Pradhan Mantri Krishi Sinchayee Yojana (PMKSY) Subsidy programmed under the Per Drop More Crop component offer capital subsidies of 45-55 percent on micro-irrigation, but marginal farmers still cannot afford installation and maintenance costs. It can be more inclusive, combining capital subsidies with group or cooperative installation schemes, an interest-saving credit facility, and guaranteed buy back schemes of crops cultivated under micro-irrigation, already tested to be successful in Maharashtra in drip irrigated sugarcane schemes (Narayanamoorthy, 2004).

5.3 Community-Based Governance and Atal Bhujal Yojana: In 2019, the most ambitious effort at institutionalizing community-based groundwater ground water management is the Atal Bhujal Yojana which was established in 2019 and implemented between 2020 with INR 6,000 crore over five years. The programmed works in 8,220 Gram Panchayats in the states of Gujarat, Haryana, Karnataka, Madhya Pradesh, Maharashtra, Rajasthan, and Uttar Pradesh and is based on the following performance incentives: releasing more funds to Panchayats that demonstrate substantial reduction in groundwater consumption and performance-based incentives: village Water Security Plans and Groundwater Monitoring Committees (Ministry of Jal Shakti, 2019). During the first year of its operation, AtBha has made considerable improvement in the groundwater monitoring capacity, community awareness, and inter-departmental convergence in the programmed districts. They however warn that recovery of aquifers at aquifer level is a 10–15-year process and programmed continuity across electoral cycles is a major weakness. (Ministry of Jal Shakti, 2020).

5.4 Traditional and Indigenous Approaches: The evidence available in the literature and field supports the importance of traditional water harvesting in a stronger manner as an affordable supplement to contemporary recharge systems. The account of Johad restoration given by Agarwal and Narain (1997) in Alwar, Rajasthan, in which the Tarun Bharat Sangh organization built more than 3,000 Johads between 1985 and 1997 and linked five of the principal seasonal rivers to the restoration of their flow is one of the most eloquent case studies of community-led environmental restoration. The hydrological principle of that distributed surface impoundments within a watershed recharge cumulatively the underlying aquifer has since been confirmed in later hydrogeological research by other authors (Kumar et al., 2005). The revival of Johad is especially the cost-effective one (cost index rating of 20 in Figure 4) due to utilization of local community knowledge, utilization of local materials and lacks in specialized maintenance. Integration of indigenous structures into formal watershed development programmed policies is a neglected opportunity.



5.5 A Systemic Framework of Sustainable Groundwater Governance: Based on the evidence that has been compiled in the current research, the Indian agricultural sector needs a combination-based framework of active operation using four supplementary pillars to implement sustainable groundwater management. The first pillar, the demand management, includes electricity tariff reform (volumetric or cap-and-trade system on pump set hours), MSP diversification to promote less water intensive crops and technology adoption support programmed to the smallholder. The second pillar, which is the augmentation of supply, includes organized recharge of aquifers by using check dams, percolation ponds and Johads combined with watershed development and where hydrologically viable, inter-basin water transfer. The third pillar called governance, and regulation demands the implementation of state groundwater legislations because of the Model Bill 2016, the creation of basin-wide groundwater institutions, and community-level governance by the means of tools such as the Panchayat committees. The fourth pillar knowledge and monitoring demand a national, digitized network of groundwater monitoring, education and extension of farmers, and investment on applied research on characterization of aquifers. A detailed overview of the strategies that were assessed under the following pillars is summarized in Table 3

Table 3: Evaluation of Sustainable Groundwater Management Strategies for Indian Agriculture

Management Strategy	Mechanism	Feasibility	Water Saved / Recharged	Cost (INR/ha)
Drip Irrigation	Precision water delivery at root zone	High	30–50% water savings	40,000–80,000
Sprinkler Irrigation	Overhead spray reducing field runoff	High	20–40% water savings	25,000–50,000
SRI (Paddy)	Reduced transplant density; aerobic soil	Medium	25–40% water savings	5,000–10,000
Crop Diversification	Shift from wheat/paddy to less-thirsty crops	Medium	15–30% savings	Variable
Check Dams	Surface impoundment for recharge	High	10–50 MCM/unit	2–8 Lakhs
Managed Aquifer Recharge	Artificial recharge shafts/wells	Medium	5–20 MCM/scheme	5–15 Lakhs
Rainwater Harvesting	Roof / farm pond collection	High	1–5 MCM/district	0.5–2 Lakhs
Digital IoT Monitoring	Real-time aquifer sensor networks	Medium	Policy enablement	10–50 Lakhs

Source: Compiled from National Water Mission (2018), CGWB (2020), Narayanamoorthy (2004), Agarwal & Narain (1997), Ministry of Jal Shakti (2019), Kumar et al. (2005), field experiment data.

6. Conclusion- The research paper contained a logical and evidence-based analysis of sustainable groundwater use management in agriculture in India based on information and literature published in 2000–2020. The very essence is identical; India is in a groundwater crisis. Since 2000, the national extraction has increased more than twice to 249 BCM in 2020. More than 17 per cent of the estimated blocks of the ground water are in the over-exploited or critical category with most of this being the northwestern agricultural belt where most foodgrain in India is produced. The aquifers of Punjab, Haryana, and Rajasthan will be depleted in two to three decades at the present depletion rates, and the potential outcomes of this will be devastating to the national food security, rural livelihoods, and ecosystem health (CGWB, 2020; Rodell et al., 2009; Shah, 2009).

The causes of this crisis are essentially structural. Combined with free electrical power to farm pump sets, MSP policies that subsidize water intensive crops, lack of property rights of ground water, and institutional weakness, these policies fail to generate a system of individual incentives which encourage collective destruction. There are technical solutions, i.e., drip irrigation, SRI, managed aquifer recharge, IoT monitoring, etc. The surveys of farmers, however, indicate that uptake is low especially in the larger proportion of smallholder farmers as a result of economic reasons, lack in knowledge, and adequate



institutional assistance. The solutions should be multi-dimensional hence the solutions should be comprised of technology and finance coupled with institutional reform and community empowerment.

The Atal Bhujal Yojana is an exciting institutional innovation, as it is a mix of performance incentives, community governance and participatory monitoring. Its effectiveness, however, requires multi-year political commitment, crossline departmental convergence, and satisfactory technical backstopping - circumstances that have traditionally been hard to maintain in Indian public programmed (Ministry of Jal Shakti, 2020). Legislation is the frontier that has not yet been conquered: without the legal frameworks that define the rights and obligations in relation to groundwater, the voluntary conservation initiatives will not be supranational against the unstoppable economic rationality of extraction.

To sum up, a sustainable management of ground water in Indian agriculture can and must be attained at such a scale of policy ambition, institutional coordination, and social mobilization as never been tried before. The window is closing once hydrological tipping points have been met, they might be serious. The evidence considered throughout this paper can be seen as a clear roadmap reform electricity subsidy, diversify crop support, invest in recharge infrastructure, strengthen community governance, enact groundwater legislation, and develop monitoring capacity which, should it be followed with determination, can see India secure groundwater and the agriculture which relies upon it in the decades to come.

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