



Techniques to Maximize Water Retention and Design Optimization of Check Dams in Rajasthan

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Abstract

Water scarcity is an escalating global issue, especially in regions like Rajasthan, India where over dependence on groundwater for agriculture and domestic use has led to severe depletion. This research investigates the question, how can the design optimization of check dams enhance water retention in arid regions, and what is their feasibility for sustainable water resource management in Rajasthan? This study integrates secondary research and controlled experiments on scaled check dam models to analyze the effect of design parameters like slope, curvature, sediment load, and Doha pits. Results show that increased curvature reduced percolation time by 16.8%, while high sediment loads reduce infiltration. The addition of Doha pits and an optimal slope improve groundwater recharge efficiency. A case study from Alwar and Sikar highlights socioeconomic benefits. Overall, well-designed check dams offer a scalable, sustainable solution for water management in Rajasthan.

Keywords: *Water retention; Check Dams; Design Optimization*

1. Introduction

Water scarcity is a growing concern affecting approximately two-thirds of the global population, especially regions with depleting groundwater levels (UNESCO, 2020). This challenge is particularly acute in India, with 54% of the country facing high to extremely high-water stress (World Resources Institute, 2019). With limited irrigation facilities, many farmers are dependent on erratic rainfall (IPCC, 2022). These extreme weather conditions, like droughts and floods, affect soil fertility and crop yields. The failure of inconsistent rainfall underscores the need for water conservation and storage solutions.

Rajasthan, India's largest state by area, is characterized by its arid climate and uneven rainfall. Most of the annual precipitation in this state occurs during a brief monsoon season, while the rest of the year remains dry. The Vyasa Committee reports that the average annual water availability in the state is just 800 cubic meters per person, far below the global water scarcity benchmark of 1,000 cubic meters.

With over 83% of irrigation dependent on groundwater, sustainable solutions for water retention are critical.

Throughout history, various civilizations have developed innovative water harvesting techniques to cope with water shortages. These include Baolis (stepwells), Tankas (underground reservoirs), and Johads (earthen check dams) have long supported agriculture through sustainable, community-driven practices (Agarwal & Narain, 1997). These traditional systems, though effective in their time, often relied on methods like field flooding, which can result in significant water wastage. In contrast, modern engineering applies hydrodynamic principles to maximize precision in water delivery. Tools such as drip irrigation and sprinklers deliver water straight to the root of the crop, minimizing water loss through evaporation and surface runoff. However, their initial installment and long-term maintenance costs compound, making them inaccessible to most rural farmers. (Postel et al., 2001).

Check dams, a type of water harvesting structure, offer a practical middle ground and have become a widely adopted solution in many parts of Rajasthan. Typically constructed on a slope, Check dams are small barriers built across natural drainage channels to capture and store runoff water. Compared to large-scale dams, check dams are low-cost, easy to construct, and cause minimal environmental damage. Overall, they offer a promising solution, but debates persist regarding their optimal design and the feasibility (Central Ground Water Board, 2020).

2. Literature Review

2.1 Historical Evolution of Check Dams

Historical evidence dates back to the use of check dams in various parts of the world, including China, Italy, Japan, France, Spain, the United States, Iran, India, Austria, Switzerland, and Ethiopia. The most notable example is the Chinese Loess Plateau, where severe soil erosion had affected nearly 60% of the land enclosed. This caused reduced crop yields, as well as severe sedimentation problems in the Yellow River. In response, the inhabitants of the Plateau ingeniously developed the check-dam system in gullies to intercept sediments, control soil erosion, improve the ecological environment, and achieve sustainable development. Check-dams, especially in the Chinese Loess plateau, have been the most effective solution for sediment reduction as well as soil and water conservation. (Xu et al., 2002)

In India, as well, the rulers of Rajasthan, during the Harappan civilization (Bronze Age), undertook several measures to conserve water. These include the construction of 'baolis', 'johads' and 'bunds', small-scale check dams, wells, and canals to ensure a sustained supply to royals and ordinary citizens. These systems were developed through observation rather than formal engineering principles but demonstrate remarkable hydraulic efficiency. (Nigam, Agrawal, & Wright, 2020)

2.2 Design Typologies

2.2.1 Temporary vs Permanent Dams

Depending on the scale of the check dam, both temporary and permanent check dams can be built. Temporary check dams are constructed on a grassroot level using natural materials such as stone, sand, logs and natural resources. While they are inexpensive and quick to construct, they require frequent maintenance and may not withstand high flow volumes during intense monsoons. Permanent check dams, on the other hand, utilize more durable materials such as cement, bricks and sandbags. These self-sustaining dams can accommodate the needs of 2-3 villages and are often integrated into broader rural development or irrigation plans. (Chaudhary & Agoramoorthy, 2008).

2.2.2 Integration of modern tools

Advancements in hydrological tools could revolutionize agricultural practices. Satellite-aided planning, such as through ISRO's Bhuvan platform or NASA's GRACE data, helps identify suitable locations by analyzing factors like soil type, aquifer recharge potential, topography, and historical water flow. (Indian Space Research Organization, n.d.; Chinnasamy, Maheshwari, & Prathapar, 2015)

Additionally, according to a 2022 report by the Central Ground Water Board, integrating GIS-based site assessments with ground surveys has improved both the cost-effectiveness and impact of check dam interventions, particularly in arid zones like Rajasthan. These innovations underscore a shift from traditional, empirical construction toward data-driven water management.

2.3 Advantages of Check Dams

Check dams are modular and require a straightforward construction process that utilizes locally available materials. These factors make these modular structures both cost-effective and accessible for the rural communities. As check dams are designed primarily to capture rainwater and reduce surface runoff, they are essential for minimizing soil erosion, preserving topsoil and improving overall land productivity. When properly maintained, these structures possess a substantial life span, enabling their effectiveness over decades. (RUVIVAL Toolbox project, n.d.).

One of the principal environmental benefits of check dams is the prevention of soil erosion. By slowing the velocity of water flow, they facilitate sediment deposition, preserving fertile topsoil essential for agricultural productivity. Furthermore, check dams play a critical role in groundwater recharge. The water impounded by these structures seeps into the soil, thereby increasing groundwater levels and improving subsoil water quality, often over a radius of 4-5 kilometers. In years with sufficient rainfall, the percolation process significantly improves subsoil moisture levels, enabling water availability for nearly twelve months. This not only contributes toward recharging of aquifers, but also the replenishment of borewells, therefore enabling long-term water security for irrigation, livestock, and domestic consumption. (Parimalarenganayaki & Elango, 2015; Zhao & Wang, 2021)

In addition to environmental impacts, check dams offer plentiful socio-economic advantages. They facilitate agricultural intensification and extensification by enabling multiple cropping cycles and improving crop quality. As a result, previously barren lands can be brought under cultivation, generating employment opportunities and increasing agricultural output. This directly supports poverty reduction as farmers can now achieve higher revenues through better yields and promote ancillary income-generating activities such as beekeeping, poultry farming, and fisheries. Overall, check dams contribute significantly to rural development by stabilizing agricultural livelihoods, reducing rural-urban migration pressures, and fostering economic resilience. (Ran et al., 2024)

2.4 Limitations of Check Dams

Both the State and Central Governments have been increasingly promoting check dams as a solution for water conservation in stressed regions, with plans to construct many new ones over the next few years. However, in many cases—such as in parts of Rajasthan—this larger watershed development has been poorly addressed, forgetting an important factor: topography. Without upstream and downstream planning, the localized impact of a check dam remains short-lived. Poorly sited structures may cause unintended problems such as waterlogging, especially in flat terrain or clay-heavy soils. Furthermore, regulatory constraints, such as government-imposed height limitations, could impact the long-term effectiveness of these dams. (Sustainable Water Resources Management, 2018).

Fundamentally, check dams are often treated as isolated solutions when they should, in fact, function as subsystems within a broader watershed management plan. Only when integrated with water conservation, afforestation, and sustainable water usage practices can they be utilized to their full potential. Maintenance is another challenge, as sediment accumulation reduces their storage and infiltration capacity over time. Regular desilting is essential but costly, and government schemes often overlook the long-term infrastructure needed for upkeep (Alhalimi, Elsayed, & Gelete, 2024).

Another critical issue is material sourcing. Due to environmental degradation and soil erosion caused by illegal mining, a landmark Supreme Court ruling has called for greater regulation. In this context, constructing check dams using illegally mined stone not only undermines environmental conservation but also contradicts the ethos of sustainable development. Concrete structures, though more expensive and resource-intensive, offer greater durability, especially during periods of erratic monsoon (Common Cause v. Union of India, 2017).

3. Implementation in Rajasthan, Case Study

To better understand the practical outcomes of check dams, a summary of a case study in Rajasthan and Haryana by PHD RDF is presented below. Conducted by third-party independent researchers, these assessments are titled ‘Survey of check dams in Alwar and Sikar districts of Rajasthan, April 2011’ and another ‘Socio-Economic Impact of Water Harvesting Structures, Nov 2015’:

Table 1: Impact Metrics in Alwar & Sikar

Serial No.	Parameters	Impact	Before Check dam (in 2004)	After Check dam (in 2014)
1.	Recharge of groundwater	35%	130	200
2.	Area under cultivation	73%	221 Hectares	383 Hectares
3.	Area under irrigation	103%	122 Hectares	248 Hectares
4.	Change in cropping pattern	Grow multi cropping 1209	Bajra, Jowar, Mustard	Wheat, peanuts, Channa, Mirch, Dalan, Bajra, Jowar, Mustard
5.	Change in number of animals	1209	1243	2452
6.	Improvement in yield of agricultural production	Wheats by 133%, Bajra and Mustard by 90%, Gram by 287%	346	818
7.	Increase in income (due to construction of check dams)	233%	52,567	1,75,136
8.	Adequacy of water from water harvesting structures	80% increased adequacy to people	Inadequate	80% increased adequacy to people

Data from the case study summarized above and reports from several regions across India reveal that check dams are indeed an effective means of water conservation and groundwater recharge. However, for long-term sustainability, certain structural and ecological challenges must be addressed. Fortunately, the majority of these problems can be mitigated through the addition of straightforward interventions.

Additionally, a substantial improvement in child education and a reduction in employment-induced migration were noticed. However, this impact analysis also revealed that regular maintenance checks are integral to the functioning of dams.

4. Design of Check Dams

The design of check dams varies based on the specific requirements of the site, including the topography, water flow, and available materials. However, the basic, overarching structural elements remain the same.

1. **Foundation-** The foundational base of the dam must be structurally stable to withstand the constant pressure of running water. Generally, materials like stone or concrete are used, depending on the soil type and local availability.

2. **Body-** The main portion of the dam is constructed using locally available materials such as stones, bricks, concrete, or sometimes even wood in smaller, traditional check dams. The body of the dam is built to a height that will slow down the water flow, allowing it to seep into the ground and recharge the water table, without causing excessive backwater flooding. In several regions in India, the maximum height without government approval is 3m to ensure water continues to flow downstream and reach other regions as well. To ensure stability, its sides are sloping, and the cross-section is usually trapezoidal, with a broader base preventing collapse. For the purpose of this experiment, the height variable will be kept constant following government regulations

3. **Spillway-** A spillway is an overflow structure built into the dam to let excess water flow safely during heavy rains. Without it, water could rise above the dam and damage it. Its size and position depend on the expected volume of runoff. If it's too small or poorly placed, water might overflow elsewhere, eroding the edges of the dam.

4. **Silt trap-** Over time, water brings along sand, silt, and debris that can clog parts of the dam or reduce its capacity. To stop this, a silt trap is placed just before the water enters the main holding area. It collects the heavier particles, which can then be removed from time to time, thereby ensuring efficiency (Soil–Soil Interface Study, 2024)

4.1 Optimizing the structure and external features of Check Dams

While designing the structure, there are several factors like the angle of inclination and water flow rate that must be kept in mind that could affect its functioning. Each of these plays a role not only in the dam's ability to hold back and slow down water, but also in how long it lasts and how much maintenance it will require.

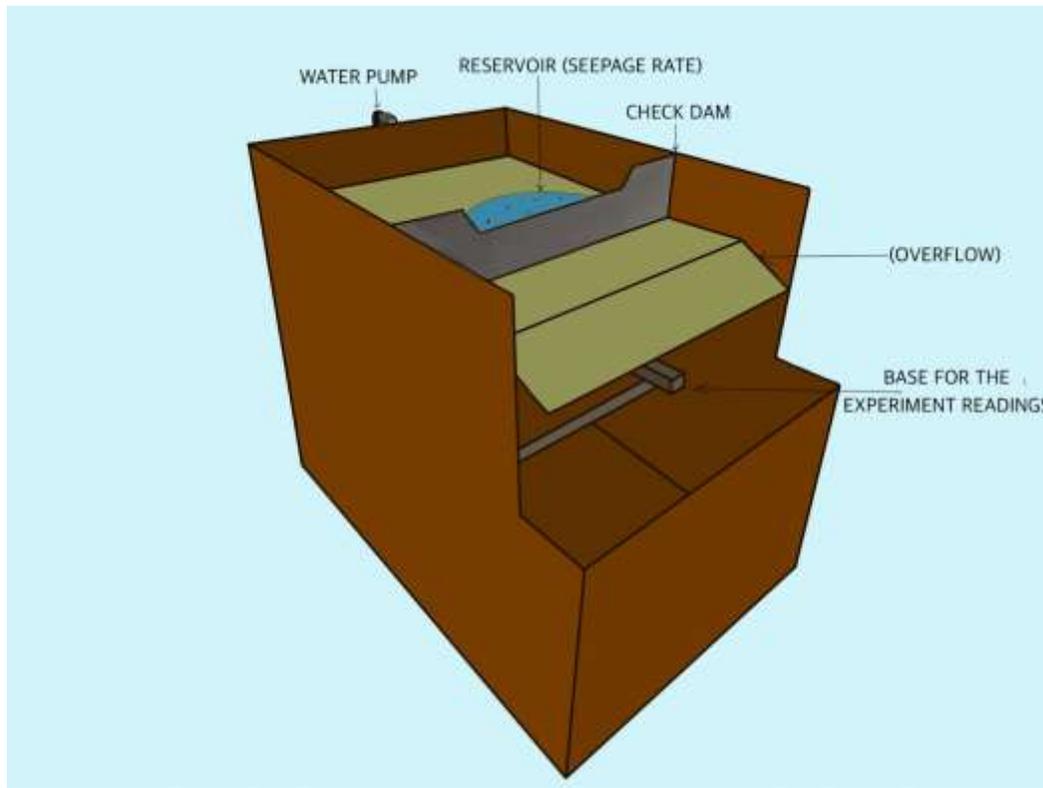


Fig 1: Diagrammatic representation of Check Dam model

4.1.1 Methodology

A series of controlled experiments were conducted on a scaled physical check dam model. The model consisted of a pump system, a check dam structure placed on an inclined platform, and a collection tray below to measure the volume of water percolated and the time taken.

A motorized water pump was used to ensure that water pressure and flow rate remained constant across trials. Only one variable was altered per trial while all other conditions were kept constant. Each trial was repeated three or more times to ensure accuracy, and the mean was taken for analysis.

Other materials used include a stopwatch, measuring cylinder, modelling clay, sediment, newspaper, protractor and scale. For all experiments, the ambient temperature, water pressure and dam height and width were kept constant.



Fig 2 : Photograph of Check Dam model

4.1.2 Results

To test these factors, I conducted a series of experiments-

Table 2: Angle of Inclination

ANGLE OF INCLINATION								
Angle	0	5	10	15	20	25	30	35
Volume of Water (mL)	250	250	250	250	4250	250	250	250
Time taken to percolate (s)	107	72	69	64	58	57	56	53
	105	69	70	61	57	54	55	51
	104.5	71	65	60	60	55	54	53
Mean	105.5	70.66666667	68	61.66666667	58.33333333	55.33333333	55	52.33333333
Median	105	71	69	61	58	55	55	53
Standard Deviation	1.32287566	1.527525232	2.645751311	2.081666	1.52752523	1.52752523	1	1.15470054
F Value: 318.890600106214								
F Critical: 2.65719660022109								
P Value: 5.75131183122626E-16								

Table 3: Sediment Load

SEDIMENT LOAD							
Sediment Load (%)	0	5	10	15	20	25	30
Volume of Water (mL)	250	250	250	250	250	250	250
Volume of water percolated (mL)	248	246	243	228	215	200	180
	247	246	241	230	213	198	177
	248.5	245	241.5	233	215	197	185
Mean	247.8333333	245.6666667	241.8333333	230.3333333	214.3333333	198.3333333	180.6666667
Median	248	246	241.5	230	215	198	180
Standard Deviation	0.763762616	0.57735027	1.040833	2.51661148	1.15470054	1.52752523	4.04145188
F Value: 495.851960784314							
F Critical: 2.84772599592536							
P Value: 1.76537437462928E-15							

Table 4: Doha Pits

DOHA PITS					
Doha pit diameter (cm)	2 pits- 5 cm each	1 pit 2.5 cm, 1 pit 5 cm	2 pits- 2.5 cm	1 pit- 2.5 cm	0 pits
Volume of Water (mL)	500	500	500	500	500
Time taken to Percolate (s)	145	147	157	162	168
	146	148	157	161	169
	144.5	150	159	161	167.5
Mean	145.1666667	148.3333333	157.6666667	161.3333333	168.1666667
Median	145	148	157	161	168
Standard Deviation	0.763762616	1.52752523	1.15470054	0.57735027	0.76376262
F Value: 257.879032258065					
F Critical: 3.47804969076523					
P Value: 4.85660091091067E-10					

Table 5: Curvature of Dam

CURVATURE OF DAM								
Radius of curvature of Dam (cm)	38	42	46	50	54	58	62	66
Volume of Water (mL)	250	250	250	250	250	250	250	250
Time taken to percolate (s)	68	67	67	62	61	59	60	57
	71	67	66	63	60	58.5	59	58
	69	68	65	62	60.5	60	58	58
Mean	69.33333333	67.33333333	66	62.33333333	60.5	59.16666667	59	57.66666667
Median	69	67	66	62	60.5	59	59	58
Standard Deviation	1.52752523	0.57735027	1	0.57735027	0.5	0.76376262	1	0.57735027
F Value: 73.8532818532819								
F Critical: 2.65719660022109								
P Value: 5.47506247110599E-11								

4.1.3 ANOVA Testing

To determine whether differences between test conditions were statistically significant, a **one-way ANOVA (Analysis of Variance)** was applied to each set of experimental results.

1. **F-value:** Indicates how much the group means vary relative to the variation within groups. A higher F-value suggests a more significant difference between conditions.
2. **F-critical:** The threshold value at a given confidence level (typically 95%). If $F > F\text{-critical}$, the null hypothesis (no effect) is rejected.
3. **P-value:** Represents the probability that the observed results occurred by chance. A $p\text{-value} < 0.05$ confirms statistical significance.

In all experiments, since $F > F\text{-critical}$ and $p\text{-value} < 0.05$, the differences in water retention and percolation were found to be statistically significant.

4.1.4 Result Analysis

Angle of Inclination

The slope of the upstream and downstream faces of the dam is critical for the stability of the dam. A steeper slope may reduce the amount of material needed for construction and increase the effectiveness of the check dam, but it makes the structure more vulnerable to collapsing under pressure. A gentler, more gradual slope, especially on the downstream face, ensures water pressure is distributed more evenly and reduces the risk of erosion.

Sediment Load

Streams in arid and semi-arid regions often carry a high amount of silt and debris. If not accounted for, this sediment can quickly reduce the holding capacity of the dam and block spillways. Over time, accumulated silt may also weaken the base of the structure. Regular desilting or the inclusion of a silt trap in the structure of the dam is necessary to maintain proper functionality.

Doha Pits

Originating from the Marathi Word ‘doh’, Dohas are saucer-shaped structures dug along the length of the stream bed, spaced at certain intervals. These pits lower the base level at specific points, increasing the storage capacity of water. By extending the period during which water remains available, these pits improve recharge potential (Aggarwal, 2021).

Curvature of Check dams

Conventionally, check dams have been known to be straight, linear structures. However, if a gentle inward curve is incorporated into the design of the dam, the surface area of the dam can increase, distributing pressure more evenly along the dam wall, thus reducing the risk of lateral erosion and improves structural stability (Anilan & Akçali, 2023).

4.1.5 Other external features of check dams

1. Evaporation control using chemicals

In arid regions, especially Rajasthan, the loss of water through evaporation is the most pressing problem with sparse solutions. However, developing research indicates that by applying biodegradable chemical films, such as long-chain alcohols or surfactants, a monomolecular layer can be created on the water’s surface. This barrier reduces evaporation by lowering the rate of water molecule escape without harming aquatic ecosystems (Panjabi, Rudra, & Goel, 2016).

2. Managing Silt Accumulation

Post the monsoon season, regular desilting can combat the problem of silt accumulation. However, prevention is always more effective than post facto correction. Planting trees with deep, fibrous root systems, especially along catchment slopes, reduces soil erosion. This is particularly significant for hilly regions where the surface flow velocity is higher (Smith & Jones, 2005).

3. Water Flow Rate

The structure must be designed for both average and peak flow conditions. During the monsoon, flow rates can rise sharply, and the dam must be able to handle sudden surges. If the structure is not designed with the local flow conditions in mind, water might bypass it entirely or erode the sides and foundation. A well-placed and correctly sized spillway becomes essential in such cases, as it allows excess water to exit the dam area safely (UK Environment Agency, 2022).

4. Overflow Management Through Channels

The construction of overflow channels can safely divert excess water away, reducing the hydraulic load on the spillway and erosion along the edges of the dam. This prevents damage during heavy rainfall and flash floods. Ideally, such channels should follow the natural contour of the land to minimize excavation and allow for controlled release into adjoining fields (Lenzi & Mao, 2016).

5. Satellite Technology

The use of satellite technology, along with field surveys and hydrogeological studies, can completely transform the process of selecting dam locations. Analysis of groundwater levels, aquifer potential, soil type, topography, and historical water flow data results in better site identification. This leads to higher recharge rate, reduced likelihood of dam failure and reduction of long-term costs (Senthilkumar, Gnanasundar, & Arumugam, 2019).

6. Structural Additions

The addition of small-scale structures like shafts, weirs, and ditches can improve the functionality of a check dam system. Shafts direct water deeper into aquifers, and weirs help regulate overflow. Digging strategically placed ditches allows the excess runoff to be directed toward agricultural fields, thereby spreading the impact of a single dam across a wider area (Lenzi & Mao, 2016).

7. Check Dam Systems

Rather than building check dams in isolation, a series of dams along a stream has been empirically found to benefit wider regions. Networks can slow the velocity of water at multiple points, especially along a steep slope, reducing pressure on individual dams, increasing water percolation and decreasing soil erosion (Meshram et al., 2019).

8. Water Management

Along with water recharge, water management, defined usage of water, especially for agriculture and consumption, is vital. Accordingly, flooding of fields and unregulated withdrawal must be avoided at all costs. By encouraging modern irrigation techniques like drip irrigation and pivot systems, water wastage can be reduced. Formation of water usage groups (WEG's) can help maintain an equitable distribution of water (Yadav, Yadav, Kumari, & Asha, 2018).

5. Conclusion

5.1 Summary of Findings

This study explored how check dams, when designed optimally, can significantly improve groundwater recharge and water availability in arid regions like Rajasthan. Experimental results demonstrated that:

- Increasing the curvature of a dam may raise construction costs, but it improves structural stability and water retention by distributing water pressure more evenly. Percolation time was reduced by 16.8%.
- The addition of Doha pits enhances groundwater recharge (more than 13.7%) by increasing water storage at localized depressions.
- Reducing sediment load maintains reservoir capacity and enhances infiltration. A sediment load of even 30% can lead to decreased water percolation by over 26%.
- A greater angle of inclination up to an optimal point (15 degrees) improves the speed of water percolation while maintaining dam stability.

5.2 Policy Implications

As India moves toward becoming a water-stressed nation by 2030, with demand expected to outstrip supply by nearly 50%, the role of water harvesting structures like check dams is critical (Ministry of Jal Shakti, 2024).

Policymakers should:

1. Encourage scientific design modifications rather than replicating traditional structures without hydrological analysis.
2. Integrate check dams within watershed management plans, considering both upstream and downstream impacts.
3. Promote the use of satellite data and GIS tools in site selection and monitoring.
4. Incentivize community participation and gender-inclusive water governance, ensuring that women and marginalized communities have an active role in the decision-making, construction, and maintenance processes.
5. Develop frameworks for long-term maintenance funding, including desilting and structural repairs, rather than focusing only on construction.

5.3 Recommendations

For sustainable implementation, this paper recommends the following:

1. Design check dams with optimized curvature, angle, and spillway configurations to maximize recharge and minimize soil erosion.
2. Supplement check dams with structural additions like weirs, shafts, and Dohas to slow runoff and spread recharge impacts.
3. Implement evaporation control measures, such as biodegradable chemical films, particularly in water-scarce regions.
4. Strengthen community-led Water User Groups (WUGs) or Water Energy Governance (WEG) structures to manage usage and maintenance equitably.
5. Encourage the adoption of modern irrigation practices (drip, sprinkler systems) to complement improved water availability.
6. Foster partnerships between local communities, government bodies, and environmental scientists to ensure sustainable, scalable, and context-specific solutions.

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