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Community-Led Groundwater Stewardship Under Seasonal Scarcity

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Abstract

Seasonal groundwater scarcity presents a distinctive governance challenge because groundwater is physically concealed, hydrologically interconnected, and frequently accessed through individually controlled wells despite being dependent on shared aquifer storage. During periods of limited recharge, unrestricted abstraction can intensify competition among users, deepen water levels, increase pumping costs, reduce access for shallow-well users, and weaken the reliability of groundwater for domestic and agricultural needs. This study develops a simulation-based framework for examining community-led groundwater stewardship under recurring seasonal scarcity.

The framework evaluates five governance dimensions: shared aquifer knowledge and monitoring, seasonal demand management, equitable allocation, recharge protection, and institutional trust and rule compliance. Five hypothetical governance scenarios are compared, ranging from individualistic abstraction to integrated community stewardship combining monitoring, negotiated seasonal abstraction rules, recharge protection, and transparent allocation mechanisms. The simulated dry-season groundwater resilience index increases from 42 under predominantly individual abstraction to 88 under integrated stewardship and recharge management.

Community monitoring alone produces meaningful improvement, but the simulation indicates that information becomes substantially more effective when it is connected to collectively agreed extraction limits, priority-use rules, drought-stage responses, and mechanisms for protecting users with weaker access to groundwater. The analysis further suggests that recharge interventions cannot substitute for demand management when abstraction remains unconstrained. Sustainable stewardship therefore requires communities to understand the aquifer as a shared resource whose seasonal condition must influence individual pumping decisions. The study concludes that locally led groundwater governance is most credible when hydrogeological knowledge, social regulation, equity safeguards, and public institutional support operate together. The proposed framework offers a transparent foundation for designing and empirically testing community groundwater institutions in seasonally water-stressed regions.

Keywords: groundwater stewardship, seasonal water scarcity, participatory groundwater management, aquifer governance, common-pool resources, groundwater resilience, community monitoring, water security.

1. Introduction

Groundwater performs an essential buffering function in regions where rainfall and surface-water availability vary substantially across seasons. Wells enable households, farmers, institutions, and local enterprises to continue accessing water when streams decline, reservoirs become unreliable, or precipitation is delayed. This apparent reliability can, however, conceal a structural vulnerability. Groundwater is stored beneath the surface, responds slowly to changes in recharge and abstraction, and is often accessed through privately controlled wells even though individual pumping affects a physically connected resource. Gleeson and colleagues emphasize that groundwater is globally important yet inherently difficult to govern because it is widespread, slow-moving, largely invisible, and connected to multiple human and ecological systems.

Seasonal scarcity makes this governance problem particularly visible. During periods following limited recharge or prolonged pumping, water levels may decline and users frequently respond by increasing pumping duration, deepening wells, drilling additional boreholes, or shifting extraction to greater depths. These individual adaptations may protect a particular user in the short term while intensifying pressure on the shared aquifer. Users with greater financial capacity can often respond more effectively than households or small producers dependent on shallow or low-yield wells. Groundwater development can therefore support human development and drought resilience while simultaneously creating depletion, quality, access, and equity trade-offs if use is not aligned with the hydrogeological characteristics of the resource.

The shared character of groundwater has led researchers to examine it through common-pool resource and co-management perspectives. Sarker, Baldwin, and Ross demonstrate that overappropriation can emerge when groundwater is not governed through institutions suited to a shared resource and argue that collaborative arrangements can strengthen groundwater management when they are integrated with broader regulatory frameworks. Participatory groundwater initiatives have similarly shown the value of enabling communities to understand aquifer behavior, monitor water levels, discuss extraction patterns, and formulate locally relevant rules. Research from participatory programs indicates that technical information can improve collective understanding, although information alone may not resolve inequality or provide sufficient incentives for users to restrict pumping.

Community-led groundwater stewardship is therefore broader than awareness generation or construction of recharge structures. It involves collective interpretation of groundwater conditions, agreement on acceptable seasonal use, protection of recharge areas, prioritization among competing needs, transparent monitoring, and mechanisms for resolving disagreements. Maheshwari and colleagues show that village-scale groundwater management benefits from approaches combining hydrological understanding, community participation, monitoring, agricultural knowledge, and institutional collaboration. Elshall and colleagues likewise argue that groundwater sustainability requires a participatory science-policy interface capable of integrating hydrological processes, socioeconomic systems, uncertainty, and diverse societal values.

The present study develops a simulation-based framework for examining how progressively stronger forms of community stewardship may influence resilience during recurring seasonal scarcity. No actual groundwater levels, household surveys, pumping records, or field interventions are represented as observed study data. Instead, the analysis compares five hypothetical governance scenarios through a Seasonal Groundwater Stewardship Resilience Index. Particular attention is given to the difference between information and regulation, the relationship between recharge and abstraction, and the protection of users who may be disadvantaged by unequal well ownership or pumping capacity. The central proposition is that seasonal groundwater resilience depends not on a single technical intervention but on the alignment of hydrogeological knowledge, collective rules, equitable access, recharge stewardship, and credible institutional support.

2. Objectives of the Study

2.1 To Evaluate the Role of Community Monitoring in Seasonal Groundwater Stewardship

The first objective is to examine how shared groundwater information can influence collective responses to seasonal scarcity. Groundwater users often make pumping decisions based on the condition of their own well, which provides only a partial representation of the larger aquifer. Community monitoring can broaden this perspective by documenting water-level trends, rainfall, well recovery, pumping conditions, recharge events, and seasonal changes across multiple observation points.

The study evaluates monitoring not as an end in itself but as a governance mechanism. Information becomes more useful when it is translated into understandable seasonal indicators and connected to decisions regarding irrigation intensity, pumping schedules, domestic-use protection, recharge measures, and drought-stage restrictions. The objective therefore distinguishes passive data collection from community learning capable of influencing collective action.

2.2 To Assess the Importance of Equitable Seasonal Demand Management

The second objective is to evaluate the contribution of negotiated demand management to groundwater resilience. During seasonal scarcity, unrestricted competition can encourage individual users to secure water before others do, producing a reinforcing cycle of extraction. Community stewardship attempts to interrupt this process through locally legitimate rules that relate abstraction to available groundwater conditions.

The analysis gives explicit attention to equity because uniform restrictions can produce unequal consequences. A household dependent on one shallow well, a small farmer relying on protective irrigation, and a large well owner operating high-capacity pumps do not possess identical adaptive capacity. Effective seasonal governance should therefore consider priority uses, differential access, livelihood vulnerability, and the distribution of benefits and burdens associated with pumping restrictions.

2.3 To Examine the Combined Effect of Recharge Protection and Collective Governance

The third objective is to assess whether supply-side interventions become more effective when combined with demand-side stewardship. Recharge structures, infiltration zones, watershed restoration, rainwater harvesting, and managed aquifer recharge can strengthen groundwater storage where hydrogeological conditions are suitable. Their benefits may nevertheless be diminished when additional recharge is immediately absorbed by increased pumping.

The study therefore examines recharge as one component of a broader groundwater institution rather than as an independent solution. Integrated stewardship is defined as a condition in which recharge protection, water-level monitoring, seasonal abstraction rules, equitable allocation, and institutional accountability reinforce one another across successive wet and dry periods.

3. Review of Literature

3.1 Groundwater as a Shared and Difficult-to-Govern Resource

Groundwater governance differs fundamentally from the governance of many visible water resources. Aquifer boundaries rarely correspond neatly with private property, administrative jurisdictions, or village boundaries, while the effects of pumping may emerge at locations and times distant from the original extraction. The combination of physical interconnectedness and decentralized access creates a classic coordination problem. One user's pumping can reduce water levels or alter availability for others, while the costs of restraint may be borne individually even though the benefits are collectively shared.

Sarker, Baldwin, and Ross examine groundwater explicitly as a common-pool resource and apply institutional design principles to a co-management arrangement. Their analysis emphasizes collaboration, rules, monitoring, and institutional nesting rather than relying exclusively on individualized extraction decisions. In another groundwater-governance context, comparative examination of participatory models found that social regulation can produce stronger sustainability outcomes than approaches based primarily on knowledge dissemination when equity and collective rules are insufficiently addressed.

Shah and colleagues' work on groundwater governance also emphasizes the importance of hydrogeological scale and interdisciplinary understanding. Their analysis argues that groundwater management must move beyond infrastructure-centered supply responses toward aquifer-based and participatory governance capable of recognizing physical groundwater systems and the socioeconomic conditions that shape dependency upon them. This approach is important under seasonal scarcity because communities cannot regulate groundwater effectively if the relevant resource boundary, recharge behavior, or interactions among wells remain poorly understood.

Groundwater sustainability therefore involves more than balancing annual abstraction against a simplified estimate of recharge. Elshall and colleagues describe groundwater sustainability as a multidimensional problem involving aquifer performance, governance, socioeconomic values, ecosystems, infrastructure, and uncertainty. Gleeson and colleagues similarly caution that groundwater sustainability should be understood through an overarching systems perspective rather than reduced to isolated concepts such as safe yield, renewability, or depletion. These perspectives establish a strong theoretical basis for community stewardship models that connect hydrological evidence with locally legitimate decision rules.

3.2 Participatory Monitoring, Social Learning, and Collective Action

Participatory groundwater management has developed partly in response to the difficulty of regulating thousands of decentralized wells through conventional enforcement alone. Such approaches seek to make aquifer conditions intelligible to users and to transform groundwater from an individually perceived source beneath each property into a collectively understood resource. Rangan's review of participatory groundwater programs highlights the role of resource understanding and community protocols in improving local groundwater management.

Maheshwari and colleagues provide a detailed example of transdisciplinary groundwater engagement incorporating hydrological, agronomic, and socioeconomic information. Community members participated in groundwater monitoring, rainfall observation, field demonstrations, and communication activities designed to strengthen local understanding of groundwater conditions. The importance of such approaches lies not only in generating additional measurements but also in reducing the informational distance between hydrogeology and everyday water-use decisions. Seasonal changes become more actionable when users can relate rainfall, well depths, pumping behavior, and crop-water requirements to a shared understanding of aquifer condition.

Collective action also depends on how information is experienced. Experimental work using groundwater-related collective-action games demonstrated that interactive learning and community discussion can alter mental models of groundwater and increase the likelihood of establishing community rules. This suggests that technically accurate information is insufficient if it remains inaccessible or disconnected from local decision-making. Stewardship institutions need mechanisms through which users can interpret uncertainty, discuss trade-offs, and understand the consequences of simultaneous pumping.

Nevertheless, participatory knowledge should not be romanticized. Reviews of community groundwater initiatives identify limitations involving equity, institutional continuity, attribution of hydrological outcomes, and the difficulty of converting awareness into sustained reductions in abstraction. These findings strengthen the case for treating participation, monitoring, and social learning as necessary but incomplete components of groundwater stewardship.

3.3 Seasonal Scarcity, Equity, and Recharge-Based Adaptation

Seasonal scarcity changes both the physical and social meaning of groundwater. During relatively wet periods, differences among users may remain less visible because wells recover and pumping competition is muted. As storage declines, however, well depth, pump capacity, energy affordability, land ownership, and access to alternative sources become increasingly important. Groundwater scarcity can consequently redistribute water toward users capable of investing in deeper or more powerful extraction technologies.

Velis, Conti, and Biermann emphasize that groundwater can strengthen food security, drinking-water access, and resilience while also generating important sustainability trade-offs when extraction causes depletion or quality deterioration. This dual role is especially relevant during drought or prolonged dry seasons because the buffering capacity that makes groundwater valuable can encourage intensified dependence precisely when recharge is weakest.

Recharge enhancement can form part of the response. Legal and governance reviews identify measures including rainwater harvesting, catchment protection, artificial recharge, and protection of natural recharge zones. Managed aquifer recharge and watershed interventions can create valuable storage for future scarcity, but the social value of additional recharge depends on who can subsequently access the stored groundwater and whether extraction remains consistent with aquifer conditions.

Community stewardship therefore requires integration of recharge and allocation. If publicly supported recharge increases groundwater availability but access remains concentrated among a small number of high-capacity well owners, the intervention may improve physical storage without improving distributive equity. Participatory models that explicitly treat groundwater as a shared resource are better positioned to discuss who contributes to recharge protection, who benefits from stored water, and how seasonal scarcity should alter permitted uses.

4. Research Methodology

4.1 Simulation-Based Research Design

The study adopts a simulation-based multicriteria design because no original field dataset was supplied. The analytical setting represents a hypothetical groundwater-dependent community experiencing recurring seasonal scarcity. Water is assumed to support a mixture of domestic requirements, small-scale livelihood uses, and irrigated agriculture. Recharge is concentrated during a relatively limited wet period, while groundwater levels decline progressively during the subsequent dry season.

Five governance scenarios are evaluated. The first represents predominantly individual abstraction with little shared information. The second introduces groundwater awareness activities. The third adds community monitoring and public interpretation of seasonal groundwater conditions. The fourth links shared information with negotiated seasonal abstraction rules. The fifth combines monitoring and demand management with recharge protection, equitable allocation, transparent drought-stage rules, and institutional support.

The simulation does not assume that community stewardship eliminates natural hydrological variability. A severe rainfall deficit may reduce groundwater availability even under well-designed governance. The purpose is instead to compare the capacity of alternative institutional arrangements to reduce avoidable vulnerability and improve the collective response to scarcity.

4.2 Seasonal Groundwater Stewardship Resilience Index

A Seasonal Groundwater Stewardship Resilience Index (SGSRI) is developed using five criteria. Each criterion receives a standardized score from 0 to 100, with higher values indicating more favorable conditions for maintaining groundwater access and institutional stability during seasonal scarcity.

Table 1: Criteria and weighting structure of the Seasonal Groundwater Stewardship Resilience Index

Criterion	Operational interpretation	Weight
Shared aquifer knowledge and monitoring	Availability, credibility, and community interpretation of groundwater levels, recharge, rainfall, and pumping trends	0.20
Seasonal demand management	Capacity to adjust abstraction, irrigation intensity, pumping schedules, and lower-priority uses as scarcity increases	0.25
Equitable access and allocation	Protection of essential needs and users with weaker physical, financial, or institutional access to groundwater	0.20
Recharge and aquifer	Protection of recharge zones and maintenance of appropriate	0.15

Criterion	Operational interpretation	Weight
protection	infiltration, harvesting, or recharge interventions	
Institutional trust and compliance	Legitimacy of community rules, transparency, monitoring, conflict resolution, and interaction with public institutions	0.20

Demand management receives the highest individual weight because seasonal resilience ultimately depends on how extraction responds to declining availability. Monitoring is essential, but a community may collect excellent groundwater data while continuing to pump unsustainably. Equity and institutional legitimacy are assigned substantial weights because rules that are technically rational but socially unacceptable or disproportionately burdensome may experience low compliance.

4.3 Scenario Scoring and Analytical Limitations

Scores were assigned comparatively using principles derived from the literature rather than measured community outcomes. Individual abstraction receives low scores for shared monitoring, demand coordination, and equitable allocation. Awareness-only governance receives moderate improvement in knowledge but limited improvement in actual seasonal regulation. Community monitoring produces stronger performance because users gain shared evidence concerning aquifer condition.

The seasonal-rule scenario adds negotiated responses such as reduced irrigation during advanced scarcity, priority protection for basic domestic needs, agreed pumping schedules, temporary restrictions on expansion of high-water-demand uses, and collective drought-stage communication. Integrated stewardship adds recharge-zone protection, local recharge measures where hydrogeologically appropriate, periodic review of rules, transparent allocation procedures, and linkage with public water institutions.

The framework does not estimate actual groundwater-level recovery, storage volume, pumping cost, or recharge rate. Such values require aquifer-specific data, including transmissivity, storage characteristics, well distribution, rainfall, recharge processes, pumping records, land use, and surface-water interactions. The numerical results should therefore be interpreted as institutional-resilience scenarios rather than hydrogeological predictions.

5. Analysis

5.1 Comparative Performance of Groundwater Stewardship Scenarios

The simulated results indicate that individualistic abstraction creates the weakest seasonal resilience, with an SGSRI of 42. Under this condition, users respond primarily to private well performance rather than to the collective state of the aquifer. Monitoring is fragmented, groundwater availability is interpreted individually, and users have limited incentives to reduce extraction when neighbors continue pumping.

Awareness-only intervention improves the score to 55. This scenario reflects communities in which groundwater education is provided but formal or socially agreed abstraction rules remain weak. Users may understand that groundwater is declining while still facing incentives to protect their own crops or livelihoods through continued pumping. The result illustrates a central governance problem: knowledge can improve decision quality, but it cannot automatically resolve strategic competition over a shared resource.

Community monitoring increases the simulated resilience score to 67 because users gain a shared representation of seasonal groundwater conditions. Monitoring creates a basis for collective discussion and can reduce disagreement about whether scarcity is genuinely intensifying. However, resilience remains below the level achieved when monitoring information is linked directly with agreed behavioral responses.

Table 2: Simulated performance of alternative community groundwater governance scenarios

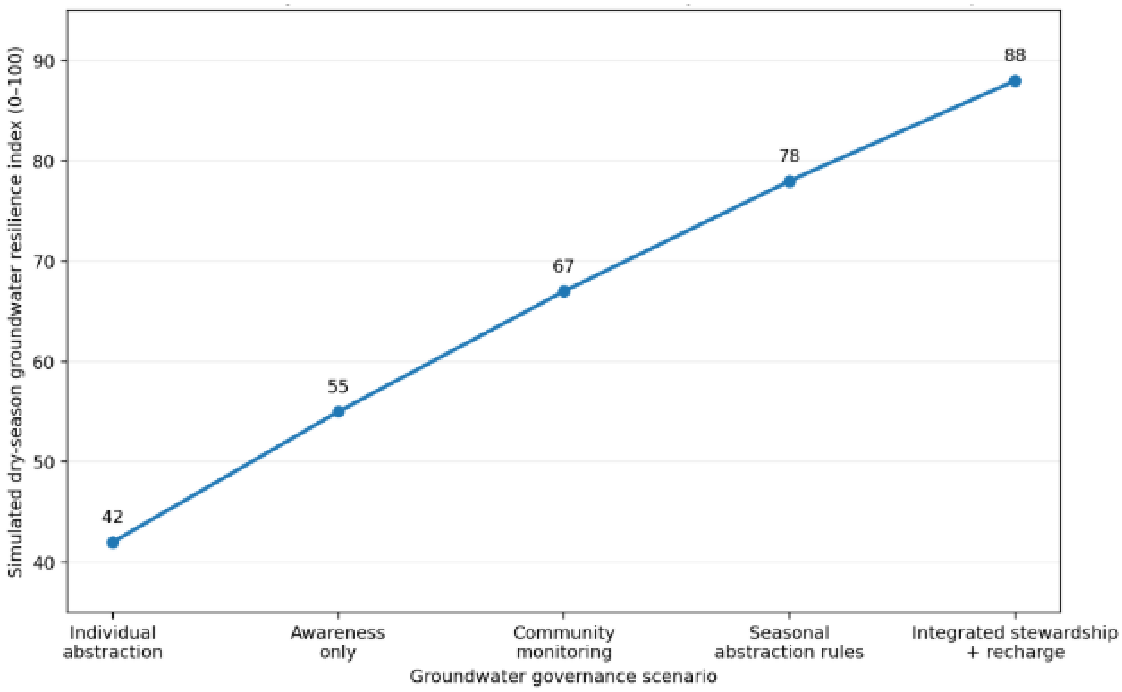
Governance scenario	Shared knowledge	Demand management	Equity	Recharge protection	Trust and compliance	SGSRI
Individual abstraction	35	32	38	48	55	42
Awareness only	65	42	50	55	62	55
Community monitoring	82	57	59	62	72	67
Seasonal abstraction rules	88	82	76	67	78	78
Integrated stewardship and recharge	94	91	87	92	86	88

The seasonal-abstraction-rule scenario reaches 78, reflecting a substantial improvement over information-only approaches. Integrated stewardship achieves the highest simulated score of 88. Its performance reflects the combined effect of knowledge, behavioral regulation, recharge protection, equity safeguards, and institutional legitimacy rather than the dominance of one intervention.

5.2 Dry-Season Resilience Across Governance Conditions

The progressive increase in resilience becomes particularly visible when the five scenarios are examined as a governance continuum. The largest conceptual transition occurs when groundwater information begins to influence actual abstraction behavior. Moving from awareness to monitoring improves common understanding, but the addition of negotiated seasonal rules produces a larger institutional change because the community begins to coordinate individual decisions.

Graph 1: Simulated Dry-Season Resilience Under Community Groundwater Stewardship



The graph should not be interpreted as evidence that a specific stewardship intervention would produce the same numerical improvement in every aquifer. Hydrogeological systems differ greatly in recharge responsiveness, storage, connectivity, water quality, and dependence upon surface water. Instead, the pattern illustrates how governance capacity can increase when progressively stronger mechanisms are added to community stewardship.

The simulation is consistent with participatory groundwater literature showing that monitoring and social learning can contribute to collective action, while more durable management requires institutions capable of connecting information with rules, incentives, and accountability.

5.3 Allocation Priorities Under Seasonal Scarcity

Seasonal scarcity requires communities to confront questions that remain less visible when groundwater is abundant. If all existing uses cannot be maintained at previous levels, a legitimate process is required to determine which uses receive priority and how restrictions are distributed. An allocation framework should generally distinguish essential household requirements from discretionary or highly water-intensive uses while remaining sensitive to local livelihood dependence.

Equity should not be defined merely as identical pumping reductions for every well. Equal percentage restrictions can disadvantage shallow-well users or small producers whose existing extraction is already substantially lower. Similarly, rules based exclusively on land ownership may exclude households without wells from decisions about a resource that affects domestic water security. Stewardship institutions therefore need representation extending beyond well owners alone.

Groundwater-sharing arrangements can also be considered where technically and socially feasible. Comparative participatory experience has shown that social regulation and water-sharing mechanisms may broaden access while reducing competitive extraction. Such arrangements require careful design because shared infrastructure, energy costs, maintenance obligations, and water-quality differences can create additional governance challenges.

6. Discussion

6.1 Why Monitoring Must Be Connected to Seasonal Rules

The first major implication is that participatory monitoring is most valuable when communities know in advance how changing groundwater conditions will influence water-use decisions. A groundwater-level record can improve awareness, but it becomes a governance instrument only when users associate particular conditions with agreed responses.

A community might, for example, define progressively stronger responses as water levels decline: voluntary conservation during early stress, restrictions on expansion of irrigated area during moderate scarcity, agreed pumping schedules during severe scarcity, and protection of essential domestic supply under critical conditions. The specific thresholds cannot be generalized because they depend on hydrogeology and local water demand, but the institutional principle is transferable.

This approach also reduces the political difficulty of imposing restrictions only after a crisis becomes visible. When seasonal rules are negotiated before scarcity intensifies, users have greater opportunity to understand their purpose and incorporate them into crop selection, household planning, or investment decisions. Such adaptive governance is consistent with broader groundwater sustainability research emphasizing participation, iterative evaluation, and explicit treatment of uncertainty.

6.2 Equity as a Condition of Groundwater Stewardship

A second implication concerns the distribution of groundwater access. Communities are rarely homogeneous. Some users own multiple deep wells, while others depend on shallow wells, shared systems, purchased water, or public sources. Seasonal decline therefore creates different levels of risk within the same aquifer.

Participatory groundwater management has sometimes been criticized for improving knowledge without adequately addressing unequal access and power. Reviews of groundwater programs indicate that equity limitations can weaken institutional sustainability even where technical awareness improves. The present simulation therefore treats equity as a core component of resilience rather than as an additional social benefit.

Inclusive stewardship requires representation of households without private wells, small and marginal users, drinking-water providers, women where they carry substantial responsibility for household water management, and other groups directly affected by seasonal scarcity. The exact institutional structure should reflect local conditions, but governance based only on the most powerful extractors risks legitimizing existing inequalities rather than managing a shared aquifer.

Allocation rules also require transparency. Communities should understand how restrictions were determined, what evidence supports them, how compliance is monitored, and what process exists for appeals or conflict resolution. These procedural dimensions influence whether water-use restrictions are regarded as collective stewardship or arbitrary control.

6.3 Integrating Recharge, Demand Management, and Public Institutions

Recharge investment is frequently politically attractive because it promises an increase in available water without immediately requiring restrictions on users. Yet recharge can create a rebound problem when users interpret increased groundwater availability as justification for expanding extraction. Effective stewardship should therefore combine supply enhancement with demand management.

Maheshwari and colleagues' participatory groundwater work illustrates the value of combining groundwater monitoring with recharge, agricultural practices, community learning, and institutional collaboration rather than treating aquifer recharge as an isolated engineering intervention. Groundwater-governance literature similarly emphasizes that recharge protection must be accompanied by broader legal and institutional arrangements.

Community leadership does not imply withdrawal of the state. Local institutions generally lack the legal authority, technical resources, or financial capacity to resolve every groundwater problem independently. Public agencies remain important for hydrogeological assessment, water-quality monitoring, drought planning, infrastructure investment, regulation of high-capacity extraction where applicable, and dispute resolution across communities sharing the same aquifer.

The strongest arrangement is therefore a nested governance system. Community institutions can provide detailed local knowledge, monitoring, rapid communication, and socially legitimate rules, while technical and regulatory agencies provide aquifer-scale science, legal support, long-term datasets, and coordination beyond village or neighborhood boundaries. This is particularly important because groundwater flow does not necessarily respect local governance boundaries.

7. Conclusion

Community-led groundwater stewardship offers a potentially valuable response to seasonal scarcity because it addresses a fundamental mismatch in groundwater governance: extraction decisions are frequently individualized even though the aquifer itself is shared. During periods of declining availability, this mismatch can encourage competitive pumping, disadvantage users with weaker access, and reduce the capacity of groundwater to provide a reliable seasonal buffer.

The simulation developed in this study indicates that groundwater resilience strengthens progressively as governance moves from individual abstraction toward shared monitoring, negotiated seasonal demand management, equitable allocation, recharge protection, and institutional accountability. The simulated resilience index rises from 42 under individualistic abstraction to 88 under integrated stewardship. These values are methodological illustrations rather than measured hydrological outcomes, but they clarify an important conceptual point: groundwater information is most useful when it changes collective behavior.

Community monitoring should therefore be designed as part of a decision process rather than as a stand-alone technical activity. Water-level observations, rainfall records, recharge information, and pumping trends need to be understandable to users and connected with predefined responses to increasing scarcity. Similarly, recharge structures should not be treated as substitutes for managing extraction. Additional recharge is most likely to strengthen long-term resilience when communities simultaneously protect recharge zones and regulate seasonal demand.

Equity ultimately determines whether stewardship institutions remain legitimate. Seasonal restrictions that protect groundwater while concentrating benefits among deep-well owners are unlikely to produce durable community support. Future empirical research should therefore combine hydrogeological monitoring with household water-access surveys, institutional analysis, gender and livelihood assessment, pumping records, participatory mapping, and evaluation of rule compliance. Longitudinal studies across multiple wet and dry cycles would be especially valuable for determining whether community stewardship improves not only awareness but also groundwater levels, access reliability, conflict reduction, and equitable distribution of scarce water.

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