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RESEARCH PAPER

Addressing Depletion in Alluvial Aquifers: Why Context Matters in Participatory Groundwater Management

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Abstract: India has one of the highest rates of groundwater extraction in the world, with depletion rates increasingly becoming a concern. The vast alluvial aquifers of the Indo-Gangetic Plain are vital for the country's food security and livelihoods of millions. However, abstraction far exceeds natural recharge, resulting in a gradual decline. The hard-rock aquifers of peninsular India are also subjected to over-exploitation. But in these low-storage aquifers, it manifests as seasonal emptying and filling. In recent years, policy attention has shifted from supply-side approaches such as watershed management to demand-side measures such as participatory groundwater management under Atal Bhujal Yojana. However, the current strategies do not account for differences in geology. We argue that the management processes that worked in peninsular Indian hard-rock systems may not be suitable for alluvial aquifers, so a different approach is needed. To make this case, we draw on Ostrom's Institutional Analysis and Development framework for the management of common-pool resources. We argue that the characteristics of groundwater resources, the socioeconomic attributes of uses and users, and the rules governing use framed by existing institutions and agrarian policies are the distinguishing features to be considered in building solutions for alluvial aquifers.

Keywords: Participatory Groundwater Management, Alluvial Aquifers, Indo-Gangetic Plain, Atal Bhujal Yojana, Agriculture, Livelihood, Sustainability

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1. INTRODUCTION

Groundwater is an essential resource for humans and ecosystems globally; it provides drinking water for billions of people, supports agricultural production, and sustains aquatic habitats through dry-season flows. However, the unsustainable use of groundwater, coupled with the changing climate and erratic rainfall patterns, has led to the depletion and degradation of groundwater resources in many parts of the world.

Globally, India leads in terms of groundwater extraction, and groundwater depletion is becoming a more pressing concern. Most of the demand for drinking, domestic use, and agricultural use water in India is met by groundwater. But both the quality and the quantity of groundwater in India are under threat. In 2004, a total of 1,615 assessment units out of 5,723 units were reported to be semi-critical, critical, or over-exploited in terms of groundwater development. By 2022, the number had risen to 2,151 units. During the same period, the number of assessment units classified as saline increased from 30 to 158 (CGWB 2004; 2022).

Continued groundwater depletion in India could have devastating impacts on food and livelihood security. Recent modelling studies have shown that food grain production could decline by 20% nationwide and by 68% in groundwater-depleted regions (Jain *et al.* 2021).

The depleting of groundwater resources has caught the attention of practitioners as well as policymakers. Over the past few decades, numerous efforts have been made by the government as well as non-governmental organizations to restore the health of groundwater resources. Despite these massive investments, the underlying groundwater problem has not been addressed.

While most current and earlier programmes, such as Jal Shakti Abhiyan and watershed development programmes, have focused on supply-side measures, in recent years, the attention has shifted to demand-side programmes. This shift has emerged from the recognition that many river basins are now closed, in the sense that all the available water is already being used. Further investments in impounding water upstream may merely result in declining amounts of water for downstream users (Molle, Wester, and Hirsch 2010).

Currently, there are two primary approaches to demand-side management programmes: (1) economic incentive–based schemes such as Pani Bachao Paise Kamao Yojana and PM Kusum Yojana, which aim to change the behaviours of individual abstractors, and (2) participatory groundwater management (PGWM)–based efforts such as Atal Jal Yojana, which rely on communities collectively agreeing on norms for abstraction.

PGWM was preceded in the 1990s by schemes such as the Andhra Pradesh Farmer Managed Groundwater System, Managed Aquifer Recharge through Village-level Intervention, and later a consortium supported by the Arghyam Foundation. The underlying hypothesis was that since groundwater is a shared resource, addressing the problem collectively will lead to collective benefits.

PGWM interventions tend to balance both demand-side and supply-side measures. However, the specific management approaches used by communities have varied across regions (Rangan 2016). For instance, in Andhra Pradesh, the focus was on participatory crop water budgeting and borewell pooling. These efforts yielded tangible advantages such as assured protective irrigation and enhanced farm income (Ramachandrudu 2015). In the district of Kachchh in Gujarat, managed aquifer recharge (MAR) emerged as the primary management intervention, leading to improved water quality (RGICS 2023). In parts of Maharashtra, PGWM involved comprehensive bans on borewells, with a sole focus on promoting the use of open wells for irrigation (Aslekar, Kulkarni, and Upmanyu 2013).

In 2019, the PGWM approach was adopted in a national programme named Atal Bhujal Yojana, which became one of the largest groundwater management schemes in the country. This was the first time that this approach was practised at scale. The programme, still ongoing, includes institutional and technological components as two important aspects of natural resources management (Bringezu *et al.* 2016; Van Noordwijk 2019). These components are represented in the programme as 'groundwater budgeting' and 'user collectives', respectively.

Groundwater budgeting is an exercise in assessing and planning groundwater resources and uses at the gram panchayat level. The groundwater balance is derived by calculating its availability and utilization. Based on the water balance, prospective demand- and supply-side activities are planned and implemented. Users' collectives are village-level institutions formed by the community where members work together to develop rules and regulations for the self-management of groundwater. By involving community members in the decision-making process, users' collectives ensure that the needs of all users are taken into account and that the management of groundwater resources is equitable and sustainable. In addition, users' collectives can facilitate the sharing of knowledge and resources among community members.

In this article, we argue that PGWM needs to be designed based on an understanding of individual and collective incentives to comply. India is geologically very diverse, and there is a need for solutions that are "fit for purpose". Though the use of both kinds of incentives have been demonstrated successfully in hard-rock aquifers, there has been some concern that they may not work in alluvial aquifers (Srinivasan 2022). While these programmes have been attempted on a pilot basis, there are barriers to scaling, especially in alluvial aquifer systems, which pose specific problems.

Management approaches that worked in peninsular Indian hard-rock systems may not be suitable for the management of groundwater in alluvial aquifers; hence, a different approach is needed. To make our case, we draw on Ostrom's Institutional Analysis and Development (IAD) framework for the management of common-pool resources (CPR). The characteristics of groundwater resources, the socioeconomic attributes of uses and users, and the rules governing use framed by existing institutions and agrarian policies are the distinguishing features to be considered in building solutions for alluvial aquifers.

2. FRAMEWORK FOR ANALYSIS OF COMMON-POOL RESOURCES

The IAD framework is particularly useful for analysing groundwater management in alluvial aquifers because it provides a structured approach for examining the complex interactions between biophysical conditions, community attributes, and institutional rules. By focusing on how these factors influence individual and collective behaviours, the framework allows for a more nuanced understanding of the challenges faced in managing CPR such as groundwater in the Indian context.

2.1. The IAD Framework

According to the IAD framework, three factors—biophysical conditions, community attributes, and the rules in use—influence the behaviours of individuals and groups in the context of management and policy initiatives that pertain to alluvial versus hard-rock systems (Ostrom *et al.* 1994; Schoon and Van der Leeuw 2015).

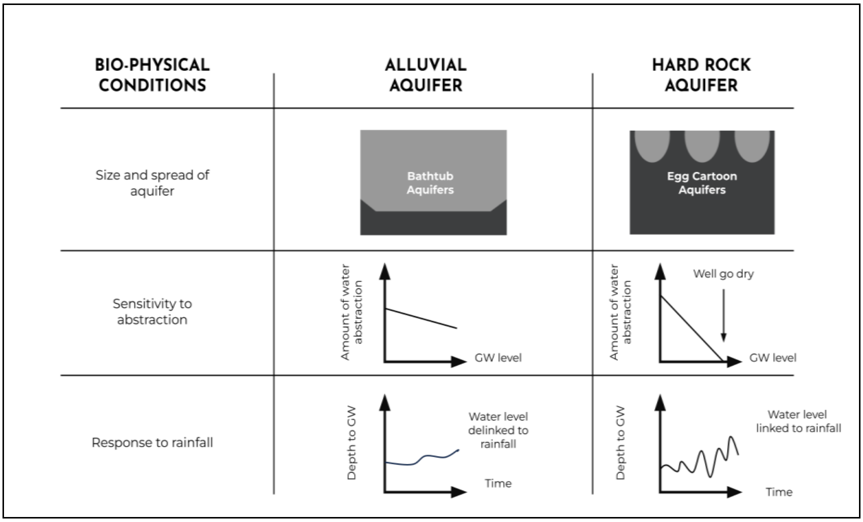
Biophysical conditions refer to the natural and physical characteristics of a particular environment or ecosystem. They play a crucial role in shaping the social and economic activities of the human communities that come in contact with them. Within the IAD framework, understanding the biophysical conditions of a particular ecosystem is important for identifying the potential challenges and opportunities in sustainable resource management.

Community attributes refer to the social, economic, and cultural characteristics of the individuals and groups who interact with a particular resource system. The IAD framework emphasizes the importance of taking into account the diversity of community attributes when designing institutional arrangements. Understanding the attributes of a community is essential for creating effective institutional systems that promote sustainable resource management.

Rules in use refer to the actual, observed set of rules and regulations that are applied by actors within a resource system. By understanding the complex and dynamic nature of the rules in use within a particular resource system, it is possible to design institutional arrangements that are better aligned with the actual behaviours of individuals and groups within that system.

In keeping with the IAD framework, the drivers and distinguishing features of alluvial aquifers can be categorized in three ways—first, by the characteristics of groundwater resources (Figure 1); second, by the socioeconomic attributes of uses and users; and third, by the prevalent rules framed by existing institutions (Table 1).

Figure 1: The Contrasting Biophysical Conditions of Alluvial and Hard-Rock Aquifers



Source: Authors

Table 1: The Drivers and Distinguishing Features of Alluvial Aquifers and Hard-Rock Aquifers in Accordance with the IAD Framework

Key Areas as per the IAD Framework	Associated Attributes	Performance in the Context of Alluvial Aquifer Development	Performance in the Context of Hard-Rock Aquifer Development	Influence over Management of Alluvial Aquifers
Biophysical conditions	Spread of the aquifer	Spread across hundreds of kilometres in length and breadth	Spread across a few kilometres or just a few metres in length and breadth	Impact on the individual is insignificant. Users are unaware of their interdependence. They also do not perceive their connection to natural phenomena such as rainfall fluctuations. This hinders local aquifer governance and the ability to build aquifer communities
	Size of the aquifer	High storativity; yield and depth to water table do not change significantly in response to abstraction	Relatively low storativity; over-abstracting causes deep cones of depression	
	Sensitivity to abstraction	Lowering the water table does not impact the amount of extraction drastically	Lowering the water table drastically impacts the amount of extraction; tubewells even go dry in the dry season	
	Response time and sensitivity to rainfall	Groundwater is stored over centuries and even millennia; the water table does not fluctuate much seasonally or inter-annually in response to rainfall	Annually replenishable; water table fluctuates with rainfall	
Attributes of the community	Resource-rich stakeholders	The users are relatively richer in terms of landholding and inter-generational wealth	The users are relatively poorer in terms of landholding and inter-generational wealth	Private interests and resource richness hinder participatory management Crop choice is influenced by the

	Absentee landlord and tenants	Almost all landowners have borewells, including absentee landlords who migrate to cities; a considerable portion of the land is managed by tenants, and the lease terms tend to stipulate fixed annual payments	Because water is scarce, borewell owners are more likely to stay within the community and lease rain-fed land; absentee landlords tend to be non-borewell-owning farmers of rain-fed land who lease their land out, and the lease terms may be fixed or based on crop-share	agrarian market and procurement policies
	The agrarian market is the driver	The prevalent water-guzzling cropping system exists mainly because of the favourable market, input subsidy, and assured price of production	Predominantly rain-fed agriculture, which lacks the support of the market, input subsidies, and assured price of production	
Rules in use	Absence of stakeholder institutions	No significant groundwater user institution exists	A long history of community-led water management and presence of user institutions; where there is strong local leadership, the community is able to exert sanctions on users who do not comply with collectively agreed-upon cropping choices	The absence of local groundwater institutions leaves a gap in collective action

Source*:* Summarized based on Ostrom *et al.* (1994), Shah (2009), Fishman *et al.* (2011), CGWB (2012), Directorate of Economics and Statistics (2018), and Srinivasan (2022).

For the purposes of this article, we are primarily contrasting alluvial and hard-rock aquifers from the perspective of PGWM. However, in fact, there are several typologies even within the Indo-Gangetic alluvial aquifer systems (Bonsor *et al.* 2017), which reflect varying geology, aquifer permeability, specific yield, groundwater chemistry (presence of arsenic and salinity), and recharge processes. Our arguments in this article are specifically confined to the over-abstracted aquifers of the "middle Indus and upper Ganges" typology (Bonsor *et al.* 2017), comprising Haryana, Punjab, western Uttar Pradesh, and parts of Rajasthan.

3. BIOPHYSICAL CONDITIONS

In analysing the biophysical conditions under which groundwater institutions operate, we need to understand the nature of aquifers in India. Aquifers are created over millions of years, but there are broadly three different ways in which they emerge. The origins of aquifers determine the biophysical conditions of groundwater flow.

An alluvial aquifer is composed of unconsolidated material deposited by rivers over millions of years. Alluvial aquifers are generally composed of sand, gravel, or similar unconsolidated material deposited by running water (Earle and Panchuk 2015). The Indo-Gangetic and Brahmaputra plains, popularly known as the Great Plains of India (CGWB 2012), are underlain by alluvial aquifers (Figure 2a). Extensive groundwater development and depletion are especially visible in Haryana, Punjab, western Uttar Pradesh, and parts of Rajasthan, and they have been widely documented as hotspots (Rodell, Velicogna, and Famiglietti 2009) (Figure 2b).

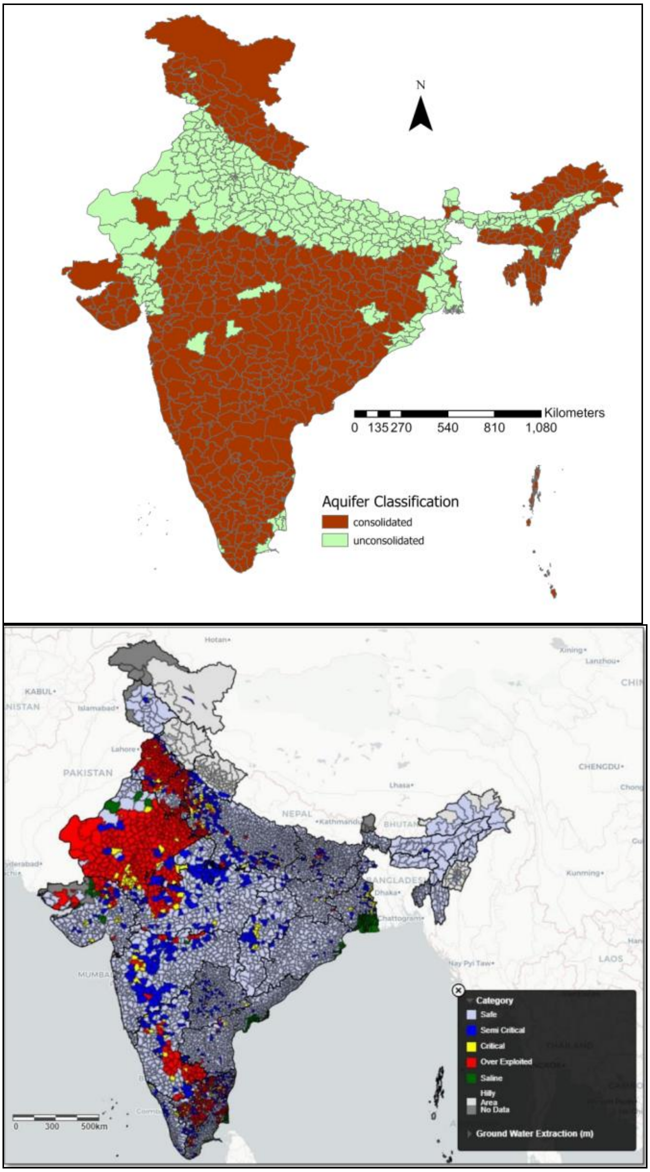
In contrast, a hard-rock aquifer or crystalline-rock aquifer emerges from volcanic or igneous rock formations that have undergone weathering processes over a long period of time. Sometimes, the alluvium may get consolidated due to the sedimentation process and become sedimentary rock, such as the sandstone aquifer in Rajasthan (CGWB 2019). For the sake of simplicity, in this article, we will broadly distinguish between the unconsolidated layers of sand and clay sediments that characterize the alluvial aquifers of the Indo-Gangetic Plain and the consolidated hard-rock aquifers of peninsular India.

According to the national compilation of dynamic groundwater resources in India (CGWB 2022), 1,006 assessment units are over-exploited and half of them lie over alluvial aquifers. Haryana, Punjab, and Rajasthan are the only states in the country where groundwater development is more than 100%. These states represent a "groundwater depletion hotspot", with 95% of India's depletion occurring here (Dangar and Mishra 2023).

Figure 2: (a) Aquifer Classification Map of India (b) Groundwater Development Stage Map of India

(a)

(b)



Note*:* Most of the over-exploited groundwater units in India are part of an unconsolidated aquifer system.
Source*:* CGWB (2022). Data are from CGWB, consolidated by WELL Labs.

On one hand, these states extract more groundwater than is recharged in an annual cycle. On the other, they contribute significantly to India's food grain production, and thus, food security. Furthermore, groundwater-based irrigated agriculture contributes significantly to livelihoods in these states (Scott and Sharma 2009). At present, 71.6% of Punjab's and 63.3% of Haryana's net areas under irrigation receive water from groundwater sources (DESA Haryana 2023; DESO Punjab 2023), and the majority of them belong to small and medium farmers.

Because the alluvial aquifer regions of Haryana and Punjab are critical for India's food security, the depletion of groundwater resources in these areas could have an adverse impact on food grain production (Bhattarai *et al.* 2021; Sarkar 2012). Furthermore, the groundwater resources in this region are highly significant from the standpoint of drinking water security and industrial growth, as the share of agriculture in India's gross domestic product is shrinking and is being replaced by that of the manufacturing and services industries.

Effective management of alluvial aquifers is an urgent necessity. Further, it is important to list the distinguishing as well as vital attributes of alluvial aquifers and the challenges associated with them in order to understand how they differ from the hard-rock aquifers of South India.

3.1 Spread of the Aquifer

To make an impactful intervention in the management of a CPR, the intervention should be carried out across the CPR unit (i.e., the aquifer).

A typical alluvial aquifer is spread across hundreds of kilometres in length and breadth and has a depth of up to a few hundred metres (CGWB 2015; Fishman *et al.* 2011; Saha, Dhar, and Vittala 2010). This means that it covers multiple administrative boundaries (gram panchayats, blocks, districts, and even states), serves various types of users (farmers, urban habitations, industries, riverine ecosystems, etc.), and could be exposed to different environmental conditions.

In contrast, a hard-rock system spreads over a smaller geographical area, often within a gram panchayat. Users have a sense of the aquifer boundaries and can observe the effects of abstraction by their neighbours. The user community is thus identifiable, and relatively easily so.

3.2 Size of the Aquifer

The cost of reversing depletion is much higher in alluvial aquifers. Groundwater depletion in alluvial systems is likely to be largely irreversible.

Alluvial aquifers are generally composed of silt, sand, gravel, or similar unconsolidated material, which means they have relatively more porous space and a high specific yield and storativity (CGWB 2015; Earle and Panchuk 2015; Shah 2009). They can store a lot of water, which can be a great boon as well as a bane. A lot of water can be extracted from an alluvial aquifer, but once it is empty, it would need an equally high amount of water to replenish it. In an era when every drop of freshwater is laid claim to, the likelihood of being able to secure large volumes of water to recharge an aquifer is very low. Furthermore, in some cases, the sediments get compressed, causing localized land subsidence along with a reduction in aquifer capacity.

3.3 Sensitivity to Extraction

The sensitivity of alluvial systems to extraction is very different from that of hard-rock systems. In alluvial aquifers, groundwater extraction per unit of time remains relatively stable (Fishman *et al.* 2011; Kumar 2018; Shah 2009). In part because of the high productive capacity of the aquifer, the water table tends to drop gradually and is not very responsive to abstraction.

Although the per-unit cost of extraction increases with the lowering of the water table, it does not significantly affect the amount of water extracted (Sarkar 2012). In some cases, the increased cost of extraction may even be compensated by the higher income earned per unit of groundwater. In general, the awareness and attention of users with regard to the depletion of resources is low, leading to negligible interest in corrective measures (Shah 2009).

In a hard-rock system, on the other hand, the water table tends to decline rapidly in response to abstraction because the aquifer productivity is low. This, at times, even results in the complete drying of the aquifer locally. This means that users are acutely aware of resource limits and are open to taking corrective action.

3.4 Response Time and Sensitivity to Rainfall

In most over-exploited areas, groundwater is pumped from deeper/confined aquifers. The literature suggests that the water in these aquifers has been accumulated over centuries and even millennia. However, the fossil groundwater is at risk of being extracted in just a few decades or even less (IIT Kharagpur 2015; Green 2016). In contrast, hard-rock aquifers fill and empty every year. They respond quickly to rainfall, which isn't the case with alluvial aquifers.

The lack of connection between rainfall and water levels in alluvial systems, and the decadal timescale of depletion, increases the chances of lock-in of unsustainable systems. Because the impacts of groundwater depletion are not directly felt, farmers may grow water-intensive crops for one or two generations, leading to permanent cultural and economic shifts.

4. ATTRIBUTES OF THE COMMUNITY (USERS)

In the IAD framework, community attributes refer to the social, economic, and cultural characteristics that influence how individuals interact with and manage common resources. These attributes are crucial for understanding the community's capacity and motivation to participate in collective action, such as managing groundwater resources in alluvial aquifers.

Farmers who live in the alluvial aquifer regions of northwestern India are relatively resource-rich; they own larger landholdings with higher agricultural productivity, which complicates PGWM efforts. Additionally, state policies promoting water-intensive crops have led to the entrenchment of this agricultural system, leading to significant groundwater depletion and minimal motivation for farmers to alter their practices.

4.1 Resource-rich Stakeholders

Because of the unique attributes of alluvial aquifers, abstraction tends to occur irrespective of the amount of rainfall and over many decades. As a result, farming communities in alluvial aquifer regions tend to be richer. They benefit from higher productivity per unit of land area as well as higher income per household.

About 90% of the total groundwater extracted from alluvial aquifers is used in agriculture (CGWB 2022). According to the agricultural census, the average landholding in Haryana and Punjab is almost thrice the national average (Agricultural Census Division 2019). Also, the average yield in these two states is higher than the national average. Furthermore, the average monthly receipt for crop production per agricultural household is approximately four times higher than the national average (Directorate of Economics and Statistics 2018). In contrast, farmers living in the hard-rock aquifer regions of Maharashtra, Karnataka, and Andhra Pradesh have relatively smaller landholdings. Also, the average income is lower as compared with Haryana and Punjab farmers.

Mancur Olson's collective action theory states that private interests and resource richness lead to the problem of free riders and thus hinder participatory management (Petrosyan 2017). Thus, considering users' relative wealth in alluvial aquifer regions and the massive economic advantage of abstracting, attempting PGWM would be an onerous task.

4.2 Absentee Landlord and Tenants

Communities with a high number of absentee landlords may lack a sense of ownership of the collective resource. A significant section of the operational area is leased in the states with alluvial aquifers. In Punjab and Haryana, the percentage of operational area that is leased is 15.2% and 26%, respectively (Bansal, Usami, and Rawal 2018). Also, in 82% of cases, the terms of the lease stipulate fixed payments. Due to the combined effect of these two factors, tenants' primary interests lie in increasing financial output rather than the sustainability of groundwater resources.

While absentee landlords are not unique to alluvial systems, there is a difference. In peninsular India, typically, only a fraction of the land in any village is irrigated as groundwater is scarce. So, absentee landlords tend to be farmers who own rain-fed land and lease it out to borewell owners. Often, these borewell owners remain in the village and continue to have a stake in the sustainability of groundwater resources.

4.3 The Agrarian Market Is the Driver

Analysis of the data shows that the cultivation of water-intensive crops is driven by the existing procurement regime (Sarkar 2020). Historically, water-intensive crops such as rice and wheat were not the primary crops in Haryana and Punjab. In Punjab, in 1960–1961, rice and wheat were cultivated on 6% and 37% of the net area sown, respectively. By 2020–2021, rice and wheat cultivation had increased to 68% and 86% of the net area sown, respectively (DESO Punjab 2023). In Haryana, in 1966–1967, rice and wheat were cultivated on 6% and 22% of the net area sown, respectively; this increased to 42% and 65% of the net area sown, respectively, by 2020–2021 (DESA Haryana 2023). In both states, the net sown area itself did not increase much over this period. The increase in the cultivation of water-intensive crops was mainly achieved by replacing less water-intensive crops such as millets and pulses. The increased water demand for these crops over the years has been met primarily by groundwater resources (Gupta 2021). The state-subsidized electricity policy acted as a catalyst in this transition (Sarkar and Das 2014).

The widespread adoption of water-intensive crops in these areas can be attributed to market forces, input subsidies, and assured-price policies such as the minimum support price (MSP). As the procurement at the MSP is primarily for water-intensive crops such as wheat and paddy, farmers—who tend to follow risk-minimizing rather than profit-maximizing practices—naturally prefer to cultivate these crops (Sharma *et al.* 2018). Of the total procurement of rice and wheat in the country, the combined share of Haryana and Punjab is 38% and 76%, respectively (Directorate of

Economics and Statistics 2018). Given the state support for these crops, the market ecosystem for credit, pesticides, fertilisers, and seeds has evolved in response, and this has created a lock-in of sorts. The cost of switching crops, even if a farmer wished to do so, would be steep.

These agrarian policies and market support has culminated in a drastic increase in the water-intensive cropping system, which in the long run, has led to the depletion of groundwater resources. This trend can be reversed only if the agrarian system as a whole were to change, altering individual farmers' incentives. There is no evidence to suggest that farmers would change their cropping decisions based on a collective decision, as PGWM requires.

5. THE INFLUENCING RULES

Groundwater being a CPR, it is vital to include users in its sustainable management. Also, groundwater requires a user-level institution to manage it and sustain collective action. According to the IAD framework, the institution should be at a scale that includes all users, and it should oversee both micro-level planning and regulation.

5.1. Absence of User Institutions

At present, there is no significant user institution in place to deal with the challenges of groundwater management in alluvial aquifer regions. Institutions such as water users' associations (WUAs) and village water and sanitation committees do exist, but these institutions are either defunct or lack the institutional capacities to take up the role of groundwater management (Chaudhuri *et al.* 2021; Kantar Public 2022).

There are two additional types of institutions that are relevant to the socio-political and water–agriculture domains in northwestern India. First, the *warabandi*[1] system and WUAs manage canal water distribution, but they are limited to surface water management, largely excluding groundwater (Narain 2008). Despite their established role, they do not directly engage with groundwater regulation under programmes such as PGWM.

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[1] A traditional system of rotational water allocation in irrigation canals, commonly used in South Asia, particularly in northern India and Pakistan, to distribute water equitably among farmers based on a predetermined schedule.

Second, farmers' unions (e.g., *kisan sabha*) and *khap*[2] panchayats are powerful sociopolitical entities advocating for farmers' interests. While they played a key role in the 2021 farmer protests (Chatterjee 2024; Punia 2022), their focus remains on immediate economic benefits, such as free electricity for agriculture, rather than long-term groundwater sustainability (Gaon Connection 2020). Though not formally integrated into groundwater governance structures such as PGWM, these sociopolitical institutions offer significant research potential. Understanding their role in either supporting or resisting ecological sustainability, alongside factors such as class, caste, and gender dynamics, could provide key insights into groundwater governance across different aquifer systems.

The absence of user institutions suggests that the currently uptake of PGWM is entirely dependent on farmer self-interest. Whereas in the case of hard-rock aquifers, farmers are able to perceive the impact of not acting collectively, and thus are motivated to collectivize, no such "natural" driving factor exists for alluvial systems. While farmer self-interest is a significant factor in explaining the lack of effective user institutions, broader sociohistorical and policy factors may also have played a role (Agrawal 1994; Bardhan 2000). The historical context, combined with the influence of caste structures and government policies, may have influenced the lack of social cohesion and collective action in groundwater management. These factors may further complicate the formation and sustainability of user institutions.

6. DISCUSSION

Contemporary efforts to address depletion in alluvial aquifers have focused on either the watershed management approach (supply-side) or PGWM (demand-side). Interestingly, both approaches originated in the context of hard-rock aquifer systems, but they are being recommended for the management of all types of aquifer systems.

The whole concept of PGWM is premised on the idea that farmers have an incentive to comply with collective cropping and irrigation decisions. But this approach is failing to deliver results in the alluvial aquifer systems of North India (Kumar 2023). The IAD analysis suggests that the massive physical spread of alluvial aquifers across multiple states, along with the lack of accuracy, efficacy, and adaptability in water budgeting methods, has

[2] A customary socio-political assembly common in northern India, particularly in Haryana, Rajasthan, and Uttar Pradesh, known for adjudicating local disputes and enforcing traditional social codes within rural communities.

caused this issue. The aquifer's biophysical conditions as well as the attributes of the community create hindrances for collective action. The users are unaware of their interdependence and lack the willingness to form an aquifer committee, either to secure the groundwater or to manage it sustainably (Shah 2009).

A single alluvial aquifer is usually shared by thousands of villages and millions of users. Even if a few villages decide to lower extraction, groundwater may still be drawn by neighbouring villages. Furthermore, alluvial aquifers do not experience much short-term fluctuations. Over-exploitation, driven by agrarian policies, does not create an immediate crisis for users. Even if a group of users in one village wished to engage in collective action, they would not be effective in controlling the decline of the water table. Nor would it be profitable for them to do so without a fundamental change in electricity and farming system incentives.

A combined analysis of resource characteristics and socioeconomic attributes suggests that the current approach of PGWM may not work in alluvial aquifers. Thus, a scheme such as Atal Jal Yojana, which is based on the PGWM system that was designed for the hard-rock aquifer systems of peninsular India (World Bank 2018), is likely to fail. If communities do not perceive the benefits of cooperation, they are unlikely to self-regulate in an isolated manner. External regulators need to set limits on groundwater abstraction for the whole system. However, this does not mean that PGWM has no role to play in alluvial aquifers. Communities may still be best positioned to enforce an abstraction limit in a participatory manner, provided the limit is set externally by a regulator.

The arguments presented in this article focus on groundwater quantity. However, the quality of groundwater can also contribute to the success of PGWM. For instance, in the coastal alluvial aquifers of Gujarat and Tamil Nadu, water quality rather than quantity is the limiting factor. Arid Communities and Technologies, a professional organization in Gujarat, has undertaken interventions in aquifers where the groundwater gets increasingly saline at depth (RGICS 2023). Here, farmers can and do perceive immediate benefits from localized improvements in water quality through MAR and controls on abstraction and thus have an incentive to cooperate.

7. CONCLUSION

The groundwater crisis in India has not been sufficiently examined. There are very few solutions designed to address the challenges posed by the alluvial aquifers of Haryana, Punjab, and Rajasthan. The CGWB, India's main groundwater management body, has compiled a compendium of best practices and solutions, containing hundreds of case studies (CGWB 2023). Likewise, the NITI Aayog, the apex public policy think-tank of the Government of India, recently released a compendium of best practices in water management in India (NITI Aayog 2021). This compendium has sections with case studies from the groundwater and agriculture domains. But in both compendiums, there are no case studies on the alluvial aquifers of Haryana and Punjab or similar typologies.

Alluvial aquifers play an important role in the lives and livelihoods of millions of farmers in India. Importantly, they are also critical for the country's food security. Policies and practices that evolved from the Green Revolution explicitly aim at exploiting these aquifers. While they were responsible for raising millions out of poverty, these policies are now a threat to livelihoods. They have locked these north-western states into rice and wheat cropping systems that have an evapo-transpirative demand far above annual rainfall. These policies are now causes for concern as groundwater tables drop. Sustainable groundwater governance of alluvial aquifer systems is the need of the hour. However, caution is required as well: alluvial aquifers are different from the hard-rock systems of peninsular India.

Policy reforms that ignore the local context are doomed to failure (Polski and Ostrom 1999). Understanding how user behaviour changes in different types of aquifer systems is key to solving this problem (Srinivasan 2022). It is important that policymakers consider the groundwater resource characteristics and the socioeconomic attributes of users in alluvial aquifer regions and how they contrast with those in hard-rock aquifer regions. This requires interdisciplinary teams. While hydrogeologists obviously understand these differences well, they may not be familiar with institutional design principles in the context of CPR. In other words, it is not enough to mandate collective decision-making; biophysical and socioeconomic conditions must also be conducive.

There needs to be dedicated investment in research and innovation to derive solutions as well as build proof of concepts, drawing on diverse expertise. Furthermore, the agrarian system should be considered central and should evolve by enhancing natural resources without compromising the well-being of farmers. Recently, Haryana started the Mera Paani Meri Virasat scheme to shift cultivation from paddy to non-paddy crops by providing financial incentives and institutional support to farmers. More such efforts should be initiated at a larger scale with systematic support.

However, the focus should be on contextual design rather than copy-pasting solutions from one region to another.

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