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Combining and Crafting Institutional Tools for Groundwater Governance

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ABSTRACT

How could having farmers play experiential games contribute to improving groundwater governance? These games are an example of an innovative procedure, a policy instrument or institutional tool, which those involved in improving groundwater governance could use to understand their problems and opportunities; consider and possibly agree on norms or rules that might avoid aquifer depletion, and create shared gains that use water more productively. Institutional tools for groundwater governance could help deal with complex nexus linkages and achieve gains such as transitions to solar-powered pumping, aquifer recharge and storage to buffer against drought, and protecting and regenerating ecosystems. The concept of a groundwater governance toolbox offers a metaphor for thinking about the variety of policy instruments available and how they might be chosen, combined, and adapted to create customized toolkits to solve problems and achieve gains in specific contexts. New policies are typically layered on top of existing sets of institutions that govern relationships between people and water. This makes it crucial to understand existing knowledge and institutions and how those may interact with institutional changes. The thesis of the paper is that institutional tools need to be combined and crafted to fit contexts, including political economy constraints, opportunities, and solutions.

Highlights:

- There are lots of institutional tools for groundwater governance, but no panaceas, and successes are rare
- Groundwater games, in combination with other policy instruments, may sometimes stimulate farmers and communities to reduce groundwater extraction
- Groundwater co-management can combine stakeholders' knowledge, values, and collective action with external science, resources, and authority
- Those governing groundwater can learn from many sources, including their own knowledge and experience, examples, stories, design principles, models, and studies
- Combining and crafting institutional tools can create toolkits for governance that fit contextual conditions and help achieve nexus gains

Keywords: institutional tools, policy instrument mixes, groundwater governance, water-energy-food-ecosystems nexus, transitions to solar-powered irrigation, managed aquifer recharge, conjunctive irrigation management, groundwater-dependent ecosystems

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ACRONYMS

IFPRI	International Food Policy Research Institute
ICRISAT	International Crops Research Institute for the Semi-Arid Tropics
FES	Foundation for Ecological Security
GDES	groundwater dependent ecosystems
MAR	managed aquifer recharge
WEFE	water, energy, food, and ecosystems nexus
WP4	Nexus Gains Initiative Work Package 4 on strengthening nexus governance

1. INTRODUCTION

Groundwater, which comprises 99% of Earth's liquid freshwater, provides nearly half the drinking water, 40% of irrigation water, and one third of the industrial water supply globally (Global Groundwater Statement 2019). Yet, governance of this critical resource is complex, multi-faceted, and engages with important opportunities and challenges (IGRAC 2018).

Solar-powered groundwater pumping can enable farmers to grow food and earn income while also reducing greenhouse gas emissions. However, it risks accelerating inefficient, inequitable, and unsustainable aquifer overexploitation, unless better governance of groundwater can create pathways to just and sustainable futures for solar-powered irrigation (Shah et al. 2018; Lefore, Closas, and Schmitter 2021). Water stored in aquifers already helps buffer farmers and other water users against variable rainfall including extremes of drought and flooding that will worsen with climate change (Steenbergen, Tuinhof, and others 2010). Managed aquifer recharge can help replenish groundwater, at multiple scales from farms and communities to landscapes (Zheng et al. 2021; Dillon et al. 2022). However, ensuring that enough water will be available in times of need also depends on institutions governing use of aquifers. Groundwater extraction can dry up landscapes, impacting groundwater-dependent ecosystems in and around springs, ponds, wetlands, streams, and rivers, along with shallow wells used for domestic water supply and irrigation (Saito et al. 2021; Eamus et al. 2016). Conversely, changes in irrigation governance that consider ecosystems, replenish aquifers, and balance multiple needs could also protect or restore flows for ecosystems. These nexus linkages between water, energy, food, and ecosystems illustrate complexities, as well as how better governance of groundwater could make a difference.

Groundwater is challenging to govern for multiple reasons. Groundwater is a common pool resource, where each person subtracts from what is available to others, and access is hard to control. In many cases, hundreds or thousands of farmers pump water from an aquifer using privately-owned wells. Each farmer's withdrawals are hard to observe. Individually, they may seem to make only a tiny difference in resource use. In contrast to surface water, groundwater is "invisible." Groundwater is a mobile resource (Schlager, Blomquist, and Tang 1994) with stocks in aquifers that are often poorly understood, complex flows of recharge and discharge with long time lags, and additional complexity related to water quality. Problems often emerge as installation of tubewells (boreholes) and mechanized pumping result in large-scale withdrawals. Declining aquifer levels can increase pumping costs, dry up neighboring wells including those supplying drinking and domestic water, deplete reserves that could buffer drought, reduce flows to ecosystems and downstream water users, and may cause other aquifer problems such as subsidence, salinization, or groundwater contamination with arsenic or fluoride. Wealthier farmers are better able to invest in deepening their wells while poorer smallholders are more at risk of losing out.

Shared use of an aquifer creates a commons dilemma (Ostrom 1990; Ostrom et al. 2002; Cole and Grossman 2010). Preventing aquifer depletion and maintaining higher levels of aquifer storage might be better for everyone in the long run. However, each individual faces temptations to maximize their own short-term benefits. In many cases, intensive groundwater use has led to continuing declines in aquifer storage, with governance institutions that have not yet been able to successfully cope with multiple and sometimes conflicting interests in order to achieve shared gains.

By comparison, surface irrigation has activities that already bring users together, to build and maintain canal infrastructure, and to distribute water and resolve conflict conflicts among users. Groundwater extraction is typically individual and so does not develop such social capital. However, acquiring additional water for recharge and managing its use can come through collective action. This also applies to obtaining water to supplement or substitute for groundwater.

There are many different institutions for governing groundwater (Theesfeld 2010). Governance, understood as the exercise of power, authority, and decision-making to manage the collective affairs of a community, society, or nation, can be formal or informal (Kosec and Resnick 2019). Institutions can be seen as “rules of the game” governing what people do, including defining roles (social positions), relationships, and what is allowed, required, or forbidden (North 1990; Ostrom 1990; 2005). Groundwater governance comes not just from actions by governments but also from the larger set of users and organizations who may act to influence how groundwater is used, who gains or loses, and how norms and rules that affect groundwater use are established and modified.

A key finding from research on governing commons has been that there is no panacea, no single tool or standard set of rules and other tools that always works, everywhere, for irrigation, forestry, fisheries, or other common-pool resources (Ostrom, Janssen, and Anderies 2007; Ruth Meinzen-Dick 2007). Groundwater is particularly challenging to govern. Examples of success, such as reducing or reversing aquifer depletion, do exist but are relatively rare (Molle and Closas 2016). Communities have governed shallow wells and springs with customary rules such as well spacing and protection zones, but these often become inadequate when mechanized pumps extract large quantities of water from tubewells (Van and Shah 2003). Conventional regulatory tools such as licensing, metering, and quotas are often ineffective in the face of powerful political and economic interests (Molle, López-Gunn, and Van Steenbergen 2018). Financial incentives such as fees, taxes, or electricity pricing can be politically difficult or impossible to apply, while subsidies may be hard to target, inefficient, or counterproductive (Shah 2009; Grafton et al. 2018). Informational instruments may have an influence but seem insufficient on their own (Reddy, Pavelic, and Reddy 2021). Using institutional tools effectively to improve groundwater governance may depend on choosing and adapting combinations of tools that fit with conditions and objectives, developing toolkits of institutions suited to particular contexts.

Experiential games are one example of a tool for improving groundwater governance, as discussed further below (Ruth Meinzen-Dick et al. 2018; Falk et al. Forthcoming). However, different conditions may require different tools, for example a different game for surface irrigation, or a different approach for large alluvial aquifers where local scale efforts may have little impact on their own. The availability of a range of tools poses questions such as which tools to use, why, when, where, how, and, crucially, who uses, make decisions about, and gains or loses from tools?

This paper examines questions about how communities of groundwater users, organizations such as groundwater boards, and groups such as participants in multistakeholder processes, can combine and adapt institutions to improve groundwater governance. It responds to a research question asking how social learning interventions, such as behavioral games, can be linked with technical and policy measures to develop inclusive groundwater governance systems (CGIAR 2021; Uhlenbrook and Ringler 2021). The goal is to improve outcomes for nexus linkages in important water-energy-food-ecosystem systems. Three nexus linkages are of particular interest:

1) transitions to sustainable solar-powered pumping for irrigation;
2) governing aquifer recharge and storage; and
3) sustaining ecosystems as part of groundwater governance.

Section 2 presents examples of toolkits and discusses how context affects the relevance of different tools. Section 3 begins by pointing out the risk of using tools too soon, when conditions are not ripe. It then notes the long time periods often needed for changes in water governance and the potential for multiple pathways for developing groundwater governance. Section 4 describes the various kinds of policy tools, and how different institutions for water tenure and coordination may help organize collective action over longer areas and periods of time. Section 5 discusses combining local and external knowledge and care to better understand and govern groundwater commons. Section 6 looks at governing to create gains in nexus linkages including transitions to solar-powered pumping, recharging aquifer storage, and including ecosystems in groundwater governance. The appendix gives sources for information about institutional tools for groundwater governance.

2. TOOLKITS FOR CONTEXTS

Tools and toolkits

The objectives of groundwater governance and the strategies employed depend, first and foremost, on the biophysical and socioeconomic context. Much of the attention on groundwater governance is on areas with falling water tables. However, there are also areas of rising water tables that cause waterlogging and salinity, where groundwater governance might rather focus on how to lower water tables. In other areas (such as in many areas of Africa), groundwater use is not intensive, and the key governance issues may concern how to expand use in an equitable manner that also considers the multiple ways water is used and valued. The strategies and tools to be employed would also depend on the scale of the aquifer, and the capacity of governments, markets, and community organizations, among other factors.

Figure 1 illustrates a variety of tools for groundwater governance identified and analyzed by Molle and Closas (2016). They found that government efforts to control groundwater withdrawals with conventional tools such as well licensing, metering, and volumetric limits (quotas) for withdrawal were often ineffective. Co-management approaches showed some examples of success which offer insights (Molle and Closas 2020a). Even with co-management, successful cases are still rare. There is not a large body of successful cases to analyze for regularities in solutions, in statistical terms, the sample size (“n”) of successful cases is small.

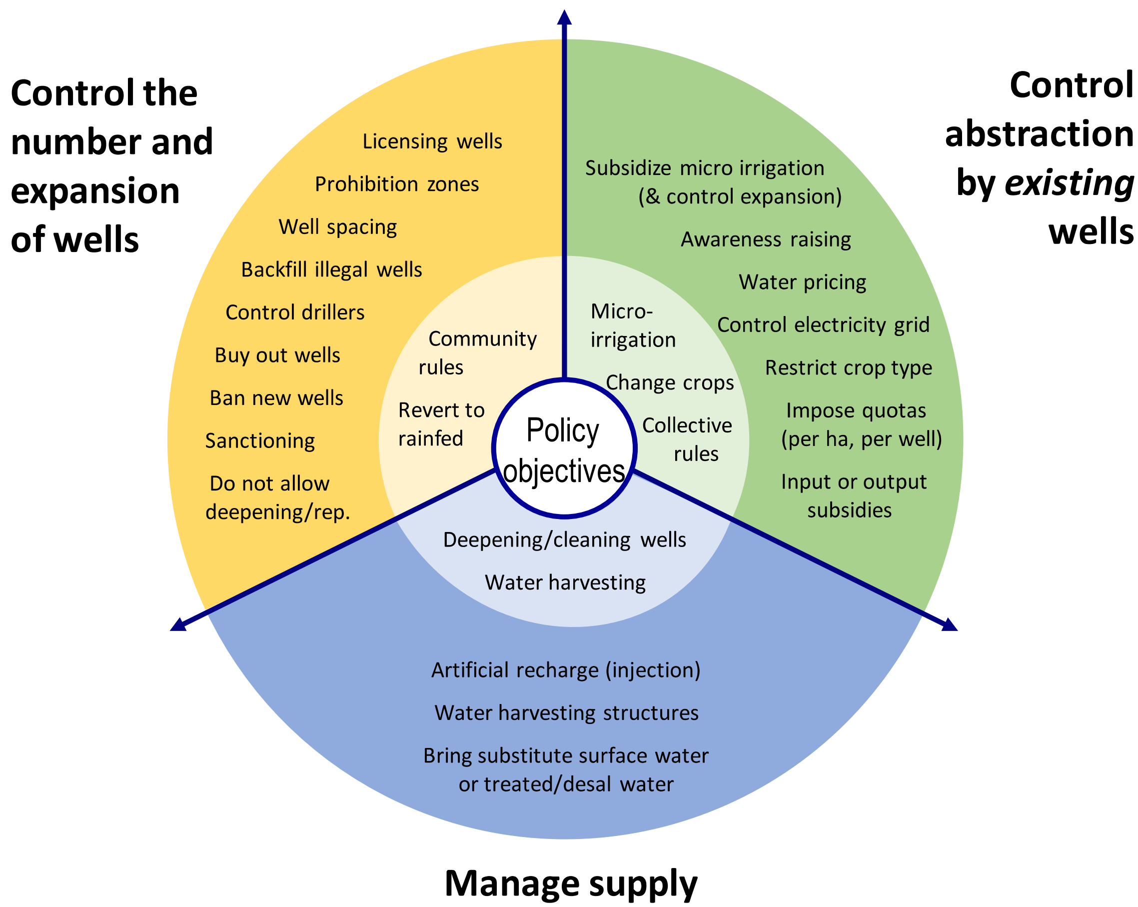

Figure 1. Policy objectives and tools for governing groundwater overexploitation
Source: Figure 1 in Molle, Lopez-Gunn, and van Steenbergen (2018), based on Molle and Closas (2016).

Tools can be combined in various ways. As discussed further below, the policy design literature often talks about "mixes" of policy instruments and how new institutional tools are "layered" on top of existing institutions (Howlett 2019). Table 1 illustrates a variety of combinations of tools, toolkits used in various efforts to manage groundwater.

Customary governance of shallow wells often relied on simple rules. These could include well spacing, protection zones around water sources such as springs, and seasonal restrictions, for example reserving pools in riverbeds for drinking or domestic water during the dry season (Van and Shah 2003). However, such customary rules have usually been insufficient to control intensive groundwater extraction from tubewells using mechanized pumps. Intensive pumping can draw down aquifer levels and follow pathways that are economically inefficient, socially inequitable, and environmentally unsustainable.

Table 1. Toolkits for groundwater governance

Customary rules	**Information-based** (Andhra Pradesh)	**North China Plain** (e.g. Hebei)
• Well spacing • Protection zone • Seasonal restrictions on water use	• Participatory monitoring of rainfall and well water levels • Crop-water budgeting • Coordination of crop selection	• Irrigation quotas • Monitoring by electricity meters • Compensation for fallowing • Replace groundwater with imported surface water
Conventional regulation	**Experiential learning** (Foundation for Ecological Security)	**Western India** (e.g. Gujarat, Punjab, Madhya Pradesh, and Maharashtra)
• Well licensing • Mandatory meters and reporting • Volumetric quotas	• Groundwater game • Education – CLART • Crop-water budgeting and crop coordination • Rainwater harvesting • Commoning (reclaiming and governing water commons)	• Well spacing rules • Watershed conservation and groundwater recharge • Restricted access and separate supply for electricity • Pilots for selling solar to grid

Sources: Customary rules (Van and Shah 2003); conventional regulation (Molle and Closas 2016); information-based (Andhra Pradesh Farmer Managed Groundwater Systems) (Venkata et al. 2013; Verma et al. 2012; Reddy, Pavelic, and Reddy 2021); Experiential learning (Ruth Meinzen-Dick et al. 2018; FES 2022; Falk et al. Forthcoming); Western India (Shah 2009; Shah et al. 2018); North China Plain (Kinzelbach et al. 2022).

Conventional recommendations for groundwater governance often assume the necessity and feasibility of licensing wells, metering to measure water usage, and volumetric quotas to limit abstraction. However, these often turn out to be infeasible or ineffective and highly constrained by political economy, suggesting the need to consider what might be done differently (Molle and Closas 2020c; 2021). While such tools ultimately might be part of groundwater governance, the timing of when tools are introduced may be crucial for effectiveness. Introducing them when conditions are not suitable, for example without capabilities for effective monitoring and enforcement, may lead to widespread avoidance, evasion, and corruption that discredits future action to govern groundwater. There are multiple options and issues to consider in trying to get a workable understanding of existing groundwater use and to monitor and influence changes groundwater extraction. An overemphasis on establishing a formal regulatory apparatus may neglect opportunities for more pragmatic and targeted measures that could have more impact.

In contrast to focusing on regulation or financial incentives, the Andhra Pradesh Farmer Managed Groundwater Systems Project emphasized information and voluntary cooperation (Venkata et al. 2013). This included participatory monitoring of rainfall and well water levels, with results publicly posted; crop-water budgeting meetings for multiple villages in hydraulic units; and coordinated decisions to grow less water intensive and more lucrative crops. During project implementation, these seem to have made a difference in farmers' understanding and actions. However, formal organized activities were not continued after the project and subsequent evaluation did not detect impacts on groundwater depletion (Verma et al. 2012; Reddy, Pavelic, and Reddy 2021). This case offers useful examples of informational and voluntary activities, but suggests these were insufficient when applied without other measures.

In India, many watershed conservation efforts have carried out works that recharged aquifers. These have been done by communities, sometimes supported by religious leaders, politicians, non-government organizations, and state governments, as well as through government projects (Shah 2000; Richard-Ferroudji, Raghunath, and Venkatasubramanian 2018). Under the right conditions, these may augment supplies of groundwater. However, investments are vulnerable to corruption and elite capture. Designs done without adequate consultation and understanding of local knowledge and conditions may miss opportunities and fail to achieve objectives. Many of the anticipated benefits may not be realized unless there are institutional arrangements sufficient to ensure participation in design, management, and maintenance, and equitable and sustainable access to recharged water.

The experience of the Foundation for Ecological Security (FES) offers one example of how tools can be combined (FES, ICRISAT and IFPRI 2021). This NGO has been working in thousands of communities in India to strengthen collective management of land and water commons. Communities often had existing rules governing use of surface water sources, but had not developed effective rules to control groundwater use. When FES found that conventional "teaching" about groundwater management did not have a sufficient impact, they piloted games played by groups of farmers as experiential learning to help improve understanding and cooperation over groundwater (Ruth Meinzen-Dick et al. 2016; Falk et al. Forthcoming). In community debriefing after the games, participants discussed how the games related to their experiences with groundwater, and community resource persons presented information about water table trends. Many communities then adopted their own rules to limit groundwater extraction. This created demand for information on alternative crops with lower water consumption, so FES created an Android app for Crop Water Budgeting as a community process. FES also helped communities use funding and technical support from the Mahatma Gandhi Rural Employment Guarantee Act and the National Bank for Agricultural Development for rainwater harvesting and watershed conservation activities to increase groundwater recharge. This included developing a Composite Landscape Assessment & Restoration Tool, an Android app, to help understand soil and water conditions and plan conservation measures (FES 2022). This example illustrates how groundwater games can be a tool added together with other tools as part of a process to strengthen local capacity to govern natural resources.

In India, restrictions on new well construction in areas where groundwater use exceeds estimated recharge have been difficult to implement. Subsidies for electricity, including low or flat rates (where farmers pay no extra cost regardless of how much electricity they use) have been blamed for contributing to overextraction of groundwater (Birner, Gupta, and Sharma 2011) The presumption is that higher marginal electricity charges would reduce groundwater overextraction (although it is not clear whether or to what extent pricing by itself would, hypothetically, be sufficient to halt or reverse overextraction). Strong political opposition seems to make changing rates or even metering electricity use impossible in many states (Mukherji and Shah 2005; Mukherji 2022a). Some states in western India, took an indirect "second best" approach by separating electric supplies for irrigation. They were then able to limit times where electricity would be available for pumping (Shah et al. 2018). More recent efforts related to electric infrastructure have involved pilots, now being expanded, that enable farmers to sell solar-power to the grid so they have an incentive to pump less. Watershed conservation programs provide an additional strategy to increase groundwater recharge.

In the North China Plain, Kinzelbach and colleagues (2022) examined experience with many measures to control groundwater exploitation. They concluded that the combination of the measures that have been applied in some sites demonstrates a path to sustainability. These include replacing deep groundwater extraction for domestic supply with imported water (for example from the South-to-North project), regional imports of surface water for irrigation to replace groundwater, payments for farmers to leave land fallow in the winter season, quotas to allocate allowable water use, and using electric meters to measure water extraction. While prepaid cards have been used to limit pumping in other parts of China (Aarnoudse and Bluemling 2017; Aarnoudse et al. 2017), Kinzelbach and colleagues (2022) found these were not effective in their research area. These examples illustrate a variety of institutional toolkits used in efforts to govern groundwater.

Context

The Institutional Analysis and Development framework (Ostrom 1990) provides a way to identify key contextual factors that affect groundwater use under the broad headings of biophysical conditions, attributes of the community, and rules-in-use. Biophysical conditions could encompass the type and size of the aquifer, rainfall and recharge; attributes of the community could include livelihoods, dependence on irrigation, level of education, and extent of trust and social capital. Rules-in-use would include both government regulations and community rules, but with an emphasis on those that are "in use". Whaley (2018) expands these categories in the Critical Institutional Analysis and Development framework (Figure 2). From the standpoint of groundwater governance, the addition of the political economy and discourse are important considerations when thinking about the context of any particular situation.

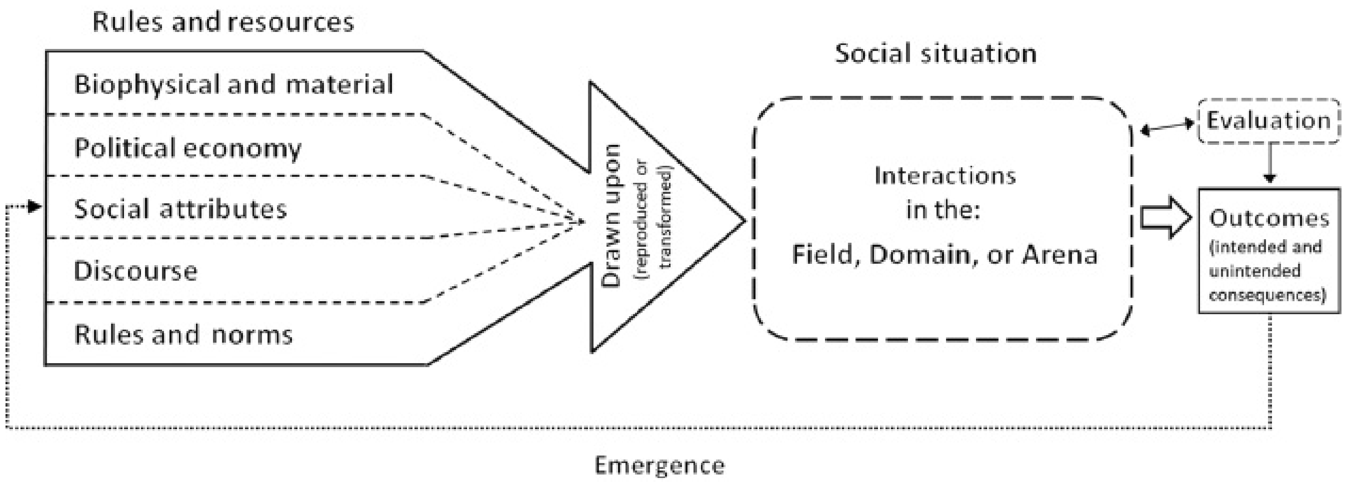

Figure 2. Critical Institutional Analysis and Development framework
Source: Whaley (2018)

Research by Elinor Ostrom and colleagues (National Research Council 1986; Ostrom 1990; Cox, Arnold, and Villamayor-Tomas 2010) drew attention to the diversity of ways in which commons were governed through rules that fit with local conditions. As mentioned earlier, researchers found that there was no panacea, no single "best practice" or "one best way" to manage irrigation systems, fisheries systems, forests, or other resources. Instead, Ostrom identified more general design principles that often characterized long-enduring locally-governed commons. These principles may also help guide groundwater governance. However, Ostrom cautioned that the design principles should not be treated as checklist that would ensure success, which depends on many additional factors. Instead she suggested the design principles might be better treated as questions to consider on topics such as social and physical boundaries, congruence (fit) between institutions and local conditions, sharing of benefits and costs, involvement of users in decisions, monitoring of resource use, enforcement of sanctions, government support or tolerance for local self-organization, and nesting of organizations at multiple scales.

Tushaar Shah's (2009) pioneering research on groundwater in South Asia highlighted how hardrock aquifers with very limited storage were conducive to collective action for recharge. Costs and benefits were localized and impacts were quick and easy to observe. However, in large alluvial aquifers, action by individual farmers or local groups could do little to affect depletion or recharge, and collective action usually took the form of political lobbying for subsidies. Shah and colleagues later examined the prospects for solar-powered pumping in India by distinguishing groundwater abundant zones and groundwater depletion zones (Shah et al. 2018). They identified eight energy-groundwater interaction settings based on differences in aquifers, rainfall, availability of canal irrigation, and market opportunities. These presented different opportunities including expanding renewable groundwater irrigation in humid areas with plentiful aquifer storage and recharge, conjunctively managing groundwater with surface water from canals, and reducing withdrawals to match long-term renewal in areas subject to depletion.

Areas with waterlogging and salinization require different approaches from areas with falling water tables. In Pakistan, where surface irrigation causes waterlogging, for example, the governance challenge is to provide large-scale drainage, such as the Left Bank Outfall Drain , and pumping groundwater may help reduce salinization (ADB 2000). In other cases, salinity may be caused by seawater intrusion, and the challenge is to balance pumping with freshwater flows to prevent salinization (Hussain et al. 2019).

Political economy structures the opportunities and constraints for changing groundwater governance (Molle, López-Gunn, and Van Steenbergen 2018). Electoral politics, and the history of how issues have been portrayed and debated shapes what may be accepted or rejected, such as power metering and pricing in South Asia (Mukherji and Shah 2005; Mukherji 2006; 2022a). The distribution of interests and power shape the difficulty of negotiating and building coalitions and agreement, the "transaction cost" of institutional change (Ayres, Edwards, and Libecap 2018). The political economy of groundwater includes the interaction of local and broader interests, and the roles of resource users and governments, for example in various forms of co-management (Molle and Closas 2020a). Social and ecological context, including political economy and power, exert a crucial role in whether and how different institutional tools may be useful in efforts to improve groundwater governance.

As a tentative generalization, the limited cases of success suggest some contexts may be particularly favorable for collective action to reduce depletion. Local communities may be able to organize watershed conservation works, on their own or with government support, that recharge aquifers where sufficient rainfall is available, such as from monsoon rains or from spate flows in more arid environments; topography, soils, and geology are conducive to infiltration, and groundwater flows relatively slowly, so local efforts yield visible local benefits (Shah 2000; 2009). A second case of favorable conditions is where saltwater intrusion threatens the water supply for cities, such as along the coasts (Ostrom 1965; Blomquist 1992). An urgent threat in such as context may result in mobilization of sufficient political support, administrative capacity, technical expertise, and financial capital to obtain water for recharge, for example by importing surface water or using treated wastewater, as well as investment in surface spreading or injection wells for managed aquifer recharge. A third type of situation is where there are already relatively strong institutions to control water allocation, such as water rights systems in areas such as the western U.S. and Spain. In some cases, pressures from downstream interests may lead to reduction in depletion in upstream areas (De Stefano et al. 2018; Esteban and Albiac 2012). Even with favorable conditions for recharge, reducing aquifer depletion is likely to require both additional water to recharge aquifers or replace groundwater for irrigation and to also require controlling demand by reducing withdrawals, either directly or through more indirect measures that influence the choice of crops and how much area is irrigated.

However, as found by (Molle and Closas 2016) in many areas where groundwater is being depleted, the standardized regulatory remedies intended to control wells and withdrawals usually fail. At present, groundwater governance is currently more art than science. The thesis of this paper is that solutions need to sought by creatively combining and crafting institutions to fit contexts and achieve gains. The structure of economic and political interests is often a key obstacle to overcome, without which regulations, financial incentives, and technical measures may be ineffective. In simpler terms, political problems require political solutions, at an appropriate scale. These may be able to unlock the potential for change when suitably combined with other measures.

Current literature on groundwater governance largely recognizes, at least in principle, the importance of tailoring governance to fit local conditions. The question is then how to do this. What set of institutional arrangements, including new and modified tools, may be helpful to improve governance so that it will work well under specific conditions? Not only is it important to consider which tools may fit with a particular context and objectives, but when and in what sequence to use tools.

3. TIMING AND SEQUENCES

Part of the ineffectiveness of conventional tools for groundwater governance may be attributed to attempts to introduce them in times and places where conditions are not yet suitable for them to be effective (Molle and Closas 2016). This includes not only technical and administrative capacity, but, most crucially, political leadership that is willing not just to enact but also to enforce new rules. That needs to be matched by a willingness of water users to comply, whether grudgingly or based on agreement about need for and value of changes (Loos et al. 2022).

In neoclassical economics, the theory of the second-best shows that if ideal conditions are not present, then attempts, such as policy reforms, that try to move directly towards first-best arrangements may make things worse (Lipsey and Lancaster 1956). Finding alternatives may lead to better outcomes. As discussed earlier, some Indian states where changes in electricity pricing seemed politically impossible were able, with some difficulty, to make changes in electric infrastructure that were politically acceptable, justified in terms of ensuring reliable electricity for households. These changes helped to ration power for irrigation and so limit groundwater abstraction. As another example for caution about the direction of change, subsidies for technical equipment to improve water efficiency and productivity at the farm level may reduce return flows for downstream water users and ecosystems and even lead to increased water abstraction for irrigation, unless combined with governance measures that can effectively limit abstraction (Grafton et al. 2018). This illustrates the need carefully consider return flows into aquifers from irrigation and other water uses and what may happen downstream and cumulatively at a basin level as a result of proposed changes.

Experience with water governance, including groundwater, shows that the time spans for institutional change are more likely to involve decades rather than years (Garduno 2005). Relatively slow flows in groundwater systems and large stocks of water in aquifers mean there it may take years or decades before impacts appear. It seems to take a long time after problems become apparent before responses occur. Even then, there may be long periods of debate and trial-and-error experimentation with various institutional reforms. Cases such as the western United States, Spain, and the north China Plain indicate that even when there is substantial technical expertise and administrative capacity, and governments that are capable of enforcing other kinds of rules, establishing and enforcing groundwater regulations is still particularly difficult.

Research on groundwater governance in the western United States, including Elinor Ostrom's (1965) dissertation, often emphasizes a pathways where the risk of having rules imposed by courts or higher level government leads local groups to finally take the initiative to work out their own agreements, protecting their autonomy and creating changes that they can make more acceptable. In other cases, change is introduced in a more top-down way, but then in some places may be taken up by local stakeholders. A comparison of four cases in Colorado found a pattern of collective action of first opposing regulation, then accepting it and trying to comply, and then in one case taking initiative to develop local regulations with a degree of success (Loos et al. 2022). However, there may well be many possible pathways. Thus, it seems worth asking what kind of political economy and political entrepreneurship could lead to successful change in different contexts?

Molle and Closas (2020b; 2020a) highlight the potential for groundwater co-management, arranging cases on a continuum in terms of state and local roles. They also note that there are at least a few cases where state-led groundwater governance has been effective. They point out the importance of triggers, such as droughts, and credible threats, such as potential top-down imposition of regulations, that could stimulate institutional reform (Molle and Closas 2016). In other words, effective groundwater governance, where is does occur, seems not to result from foresighted planning to prevent problems and instead emerges, if at all, from prolonged contestation driven by resource depletion and conflict, including efforts of downstream users or others harmed by overextraction.

The idea that crises create opportunities is a maxim of water governance (Garrick 2016). Drought, flood, or other events draw attention, from the public and from leaders and officials, and may create a willingness to consider and implement changes that otherwise would not have been accepted (Loos et al. 2022). The literature on environmental governance discusses punctuated equilibrium models (Repetto

2006) where periods of relative stability are interrupted by episodes of reform stimulated by shocks, such as extreme weather or political shifts. Changes that lead to control over groundwater extraction, whether simpler actions such as protection zones and bans on borewells or more detailed regulation of groundwater abstraction, seem like a non-linear process with a threshold after which drastic transformation occurs. This is like a phase change from solid to liquid, with the potential to take on a new form.

Putting different activities, procedural tools, in sequence along a pathway may help illustrate how tools could be combined. As a first step in efforts to improve groundwater governance it may be important to understand the existing situation. As discussed further below, assessment of water tenure—defined as "the relationship, whether legally or customarily defined, between people, as individuals or groups, with respect to water resources" (Hodgson 2016, xii; FAO 2020)-can be seen as a way of discovering the existing tool box of institutions, current rules-in-use (Ostrom 1990) and practices. Learning approaches that emphasize listening, stories, and conversations, as discussed below in section 5, can improve understanding of how people perceive and act in relation to water, including their responses to the impacts of increase groundwater extraction, such as experimenting with modified or new rules (Zwarteveen et al. 2021). Socio-hydrogeology (Huggins et al. 2022; Re et al. 2021) offers a framework for seeing where scientific knowledge about groundwater may combine with and enhance local knowledge, as a potential basis for action. Activities such as groundwater games and crop-water budgeting discussed above can improve understanding and contribute to creating agreement on actions, as can multi-stakeholder processes that link various government agencies and communities. Such forums could help formulate consensus around proposals that can then be institutionalized in policies and programs and put into practice. Table 2 provides one illustrative sequencing of tools and approaches, although this would need to be adjusted based on local conditions. Depending on time and resources, the combination of tools could be crafted to be relatively rapid and cheap, relying primarily on local knowledge with only carefully targeted external facilitation and expertise, or combine more intensive research, analysis, and processes for building mutual understanding and consensus.

Table 2. An illustrative sequence of tools and approaches

- Water tenure assessment
- Listening and learning from communities (ethnography)
- Socio-hydrogeology
- Experiential learning: groundwater games
- Crop-water budgeting
- Multi-stakeholder processes for consensus-building and collective choice
- Adaptive co-management

Source: Authors

4. INSTITUTIONAL TOOLS AND POLICY DESIGN

There are many examples and much that can be learned from the variety of institutional tools that have been used in efforts to govern groundwater. This section looks at concepts from the policy design literature that are helpful in understanding different policy instruments. This paper will use the term institutional tools largely synonymously with policy instruments, following Howlett's (2019, 136) description of policy instruments as "defined very broadly so as to include a wide range of tools or techniques of governance used at different stages of the policy process."

As part of reviewing and synthesizing research on policy design, Howlett (2019) applies a fourfold categorization of substantive policy instruments, including informational, regulatory, and financial, as well as direct provision of goods and services by government or other organizations. Howlett also draws on the policy design literature to distinguish an additional category of procedural policy tools such as requirements for public disclosure of information, environmental impact assessment, or public consultation. These procedural tools and their associated activities also illustrate how governance goes beyond action just by governments and encompasses the range of people and organizations who are involved in collective action, including decisions about how to govern aquifers. Farmers and other water users may cooperate on their own, or work together with government agencies, using a variety of rules and processes that shape who takes water, and how that water is used, and possibly protected or replenished.

In their discussion of incentives for avoiding the tragedy of the commons, Uphoff and Langholtz (1998) point to the importance of not only regulatory and financial incentives, but also socio-cultural incentives. Socio-cultural incentives may influence behavior through norms, reputation, trust, and other factors and facilitate coordination that may not necessarily rely on coercive authority or financial incentives. For example, in Pakistan, where well owners may sell groundwater to neighbors, the price and reliability of delivery are shaped by norms of sharing water with relatives and neighbors (Ruth Meinzen-Dick 1996; 2000). While such incentives may seem less amenable to being shaped, as regulatory and financial incentives may be, Falk et al. (Forthcoming) show how experiential, social learning interventions can shape mental models and norms. A socio-cultural perspective can also help understand the ways in which people care about each other and their environment, and act together on their concerns (Zwarteveen et al. 2021)

Table 3 illustrates one way of categorizing different institutional tools, primarily based on Howlett's (2019) fourfold division of substantive instruments into informational, regulatory, financial, and organizational (government or other organizations directly affecting provision, distribution, or consumption) plus procedural instruments that affect policy processes. Groundwater games are classified as primarily procedural instruments, affecting relationships and socio-cultural incentives. Impacts from playing the game together with other people would be in addition to informational impact on individual mental models that could occur if participants play a game by themselves, as sometimes was done with the game used by Kinzelbach and colleagues (2022) in China. Different forms of water tenure and water rights are elaborated under regulation, and described below, since the variety of forms and tenure and ways of adjusting them are often not adequately recognized (Bruns and Meinzen-Dick 2000; Hodgson 2016). The table also shows different kinds of organizations and networks that may be established (constituted) by governments and stakeholders, including federations and other kinds of polycentric arrangements between organizations (ElDidi et al. 2021).

Table 3. Types of institutional tools for groundwater governance

Information	**Regulation** (norms and rules)	**Financial/economic**
• Data, e.g. weather, crop water needs, crop evapotranspiration (ET) • Geographic information systems (GIS) • Decision support systems • Extension, training • Educational media • Individual educational games	• Well spacing • Well licensing • Protection zones • Volumetric controls (e.g. quotas • Crop restrictions • Irrigation schedules • Measurement (metering) • Electric connections • ET-based rules or enforcement	• Water tariffs/prices • Fees, fines • Payments to not irrigate • Energy pricing • Sell solar power to grid • Subsidies for farm inputs & outputs • Nature-based solutions (NBS)/ Payment for environmental services (PES) • Water markets
Procedural (Social learning) • Social experiential games • Crop-water budgeting • Mapping with local knowledge • Participatory hydrological monitoring • Participatory modeling, scenario analysis • Stories and conversations • Dialogue and deliberation, consensus-building • Multi-stakeholder processes	Tenure/rights • Customary rights • Commoning • Hybrid licensing • Devolution • Human right to water • Rights of nature • De minimis, subsistance rights, etc. • Environmental protection • Liability • Unitization • Leasing	**Organizational**: Direct provision (government, NGO, co-production, etc.) • Surface and groundwater irrigation systems • Managed aquifer recharge (MAR) • Research on aquifers Constitutional**:** organizations and networks • Polycentric agreements • Forums and federations • Professional societies • WUAs, RBOs, NGOs, corporations, professional societies, etc. • Advocacy coalitions • Social movements • Formal and informal social networks

Sources: Examples by authors. Most types are from Howlett (2019); constitutional (Ostrom 2005; Frantz and Siddiki 2021).

Among financial and economic incentives, there has been considerable discussion of water tariffs, prices, fees and fines to create incentives to reduce groundwater extraction. However, implementing such charges generally requires metering of water, which is difficult to achieve (Molle and Closas 2021). Pricing of energy provides an alternative indirect mechanism to create financial incentives to limit groundwater use. Not all financial incentives are negative: the possibility to sell solar power not used for pumping back to the grid can provide a positive economic incentive, as can payments to not irrigate and payments for ecosystem services. Output prices of crops with different water requirements similarly shape incentives for groundwater use.

Regulatory tools and rules may specify restrictions on groundwater use, but their impact, in practice, depends on the extent of implementation. As discussed earlier, Molle and Closas (2016) analyze experience with policy tools for regulating the number and expansion of wells, water abstraction from wells, augmentation of water supplies, and other tools.

In practice types of policy instruments and incentives may overlap or take hybrid forms, so a classification is more a convenient grouping rather than a matter of exclusive categories (Theesfeld 2010). For example, crop water budgeting tools could be considered informational, but if they are done within a community context, they could function as a procedural tool for social learning. Similarly, maps, scenarios, and computer simulation models provide information, but their creation and use can also create a framework for developing agreement about shared strategies, norms, and rules.

Distinctions between regulatory versus economic and informational instruments often focus on the "voluntary" nature of cooperation that may emerge from having shared information or in response to market incentives, in contrast to regulations backed by authority to coerce. Pure coercive authority through strict enforcement is usually difficult or impossible for controlling groundwater extraction (Molle and Closas 2020b). Cooperation with laws and regulations is often "quasi-voluntary" (Levi 1989) in the sense that cooperation depends not only on expectations about enforcement (which may be uncertain or unlikely) but also perceptions about the legitimacy and public benefits of rules, and how they fit with ideas about morality and justice. This may also come from "conditional cooperation" among those who, at least initially, expect others to also cooperate (Ostrom 2000). The threat of enforcement may sometimes be necessary, what Molle and Closes refer to as "the shadow of hierarchy." However, it may well be insufficient to ensure effective compliance with rules on its own. Instead compliance may depend on also building understanding and consensus about problems of groundwater depletion, the feasibility of solutions, and assurance that others will also cooperate.

Conversely, cooperation primarily based on norms and trust is often discussed as "voluntary." However, this can depend on informal sanctions such as disapproval, shaming, and loss of reputation, which can have serious consequences. At the extreme, being kicked out of a group, ostracism, can be a kind of "social death" that deprives someone of most of what they need in order to survive or to have a meaningful and satisfying life. This may be particularly true in small rural communities or for other tightly-knit social networks, such as may exist among traders or professional practitioners. A key indicator of feasibility may be whether farmers are ready to pressure their neighbors to cooperate, and to report or otherwise sanction those who violate rules about groundwater use.

As discussed by Howlett (2019), early policy research tended to look at policy instruments in isolation, and as if they were being introduced with a blank slate where there were no previous institutions. This disregards the extent to which any policy change occurs in a context that is already shaped by many institutions. As North (1990) emphasized, institutional change is path dependent (David 1985). Typically, new policies are "layered" on top of previous policies and other institutions (Howlett 2019). This also means that what matters are not individual policies in isolation but mixtures or portfolios of policies that may interact with each other. Consideration of a policy change is not just a matter of abstract or generic characteristics of tools, but involves the possible impact of a policy instrument or package of instruments within a particular context.

Joint activities, such as playing a groundwater game may not just improve individual understanding, as would playing an individual games, but can develop relationships that strengthen or transform socio-cultural incentives. This could occur, for example, through mutual understanding, agreeing on norms, increasing concern for how others are harmed or helped, and creating or reshaping group identities. An "institutional tool" such as a groundwater game may have an impact on its own, or in combination with other institutional changes. These impacts may be heavily dependent on the context.

If institutional tools are layered onto existing sets of institutions, then it may be crucial to understand those institutions, and how they work in context. Water tenure assessment offers one tool for identifying and then considering the existing set of relationships between people related to water which could be useful in efforts to understand and improve groundwater governance (Hodgson 2016; FAO 2020). It can both generate information and provide a process of interaction to consider institutional changes. Involvement of stakeholders, if done well, brings in their knowledge of existing institutions related to water and their assessments of how changes might work. Multi-stakeholder processes are an example of a procedural instrument that can facilitate collaboration in designing institutions for groundwater governance (Steins and Edwards 1998; Van Rooyen et al. 2017; Edmunds and Wollenberg 2001; ElDidi et al. 2021).

Water tenure

Water tenure shapes who gets water and what they can do with it. Table 3 lists institutions related to water tenure and water rights, formal and informal. A detailed discussion of different forms of water tenure is beyond the scope of this framework paper. However, a key point is the diversity of different kinds of tenure, and how they may overlap and interact, with multiple sources of rules and forums for conflict resolution (Bruns, Ringler, and Meinzen-Dick 2005; Hodgson 2016). All these create complexity in how water, including groundwater, is already governed, and the possibilities for changing governance.

Water tenure may be explicit or implicit in the institutional arrangements through which water is acquired and distributed by farmers and others. Even apparently open-access or anarchic situations may still include some forms of rights, such as landholders' right to install and use wells, based on local norms and rules and also, in many cases, national laws. Norms, religion, and other aspects of culture may shape the extent to which well-owners are or are not expected to share water, avoid harm to other wells, or protect water purity. Even where formal water rights are allocated, they may be constrained by lack of enforcement or competing laws, principles, and norms--various kinds of legal pluralism (Bruns and Meinzen-Dick 2001; R. Meinzen-Dick et al. 2007). These could include priorities for drinking water, tolerance of minor (de minimis) use, public trust limitations of what rights the government can allocate, national and internationally-recognized human rights, and regulations related to other matters, such as environmental protection. Communities may reclaim shared water bodies from state takeover or private encroachment, one kind of "commoning" (FES, IFPRI, and ICRISAT 2021). Water rights may also be transferred, by inheritance, temporary leasing, or sale. Or rights might be incorporated into a single jointly owned entity, unitization (Jarvis 2011). Hybrid water law and licensing are an example of a strategy that could be considered as a way of combining existing water tenure institutions and knowledge with more targeted changes, for example prioritizing small scale subsistence users and concentrating formal regulation on large scale users (Schreiner and Van Koppen 2018; Van Koppen 2022).

Importance of time and spatial scales

One framework for understanding different forms of groundwater governance concerns the scale and duration of coordination that may be required. Operating a well on an individual's farm may require little coordination with others, but managing the aquifer that the well draws from requires coordination. Where aquifers are highly localized, as in some hardrock aquifers in India, then action at the community scale may be sufficient to organize action, including sharing of benefits and costs (Shah 2009). Or, as in parts of Yemen, groundwater may move beyond the scale of a single settlement, but slowly enough, for example kilometers or tens of kilometers per year, so that multiple neighboring communities share the costs of overextraction and the potential benefits from reducing overexploitation or increasing recharge (Taher et al. 2012). In this case, coordination needs to cover multiple communities, while still much smaller than the scale of river basins or provinces (governorates). Many alluvial aquifers have even larger scale, and may even require coordination at international levels, as in the case of transboundary aquifers in the Aral Sea basin. Even wells that serve multiple farms require coordination, which might be by the state, by collective action if the well is jointly owned, or through informal water markets, if the well owner sells water to neighboring farmers.

Studies of collective action in the water sector indicate that where coordination is needed at the scale of a close-knit community it may be relatively easy to organize, drawing on existing trust and other relationships, "social capital," between people who expect to keep interacting with each other. However, even within a community, the invisibility of the resource makes it more difficult to coordinate than for surface water.

As scale expands in time and space, the benefits or costs become more widely distributed (and less exclusive), and there are usually fewer social connections, less social capital. In this case, formal institutions including governments become important for creating commitment and ensuring sufficient incentives to fulfill agreements and comply with rules. This can include achieving potential gains, such as access to markets for high-value crops. It could also involve resolving conflicts related to costs, such as impacts on downstream water users and ecosystems.

Figure 3 offers an illustration of the relationship between different water resources situations in relation to spatial scale and duration in time, and how different governance tools might fit to particular spatial and temporal scales. This may also apply to relationships and transactions concerning groundwater and the nexus linkages between water, energy, food, and ecosystems.

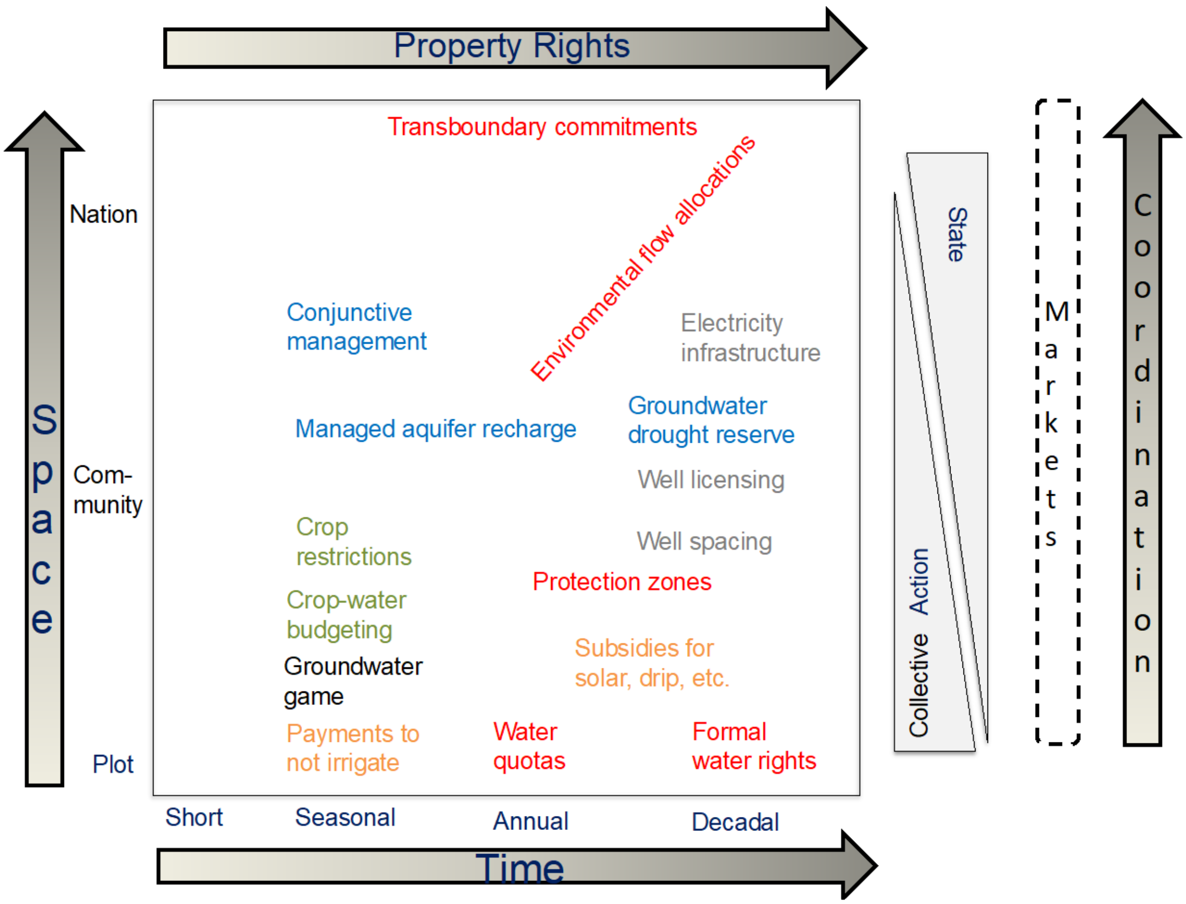

Figure 3. Property rights and coordination institutions
Source: Adapted from Meinzen-Dick (2014)

5. KNOWING AND CARING FOR GROUNDWATER COMMONS

Multiple perspectives on governing groundwater

Groundwater governance can benefit from combining local knowledge of water users and knowledge of hydrogeology, particularly for understanding how water flows in aquifers. This resembles water quality (Schlager 2005) where chemistry and microbiology are helpful and integrated pest management where entomology and ecology can provide useful additions to local knowledge. Issues of groundwater quality, including groundwater pollution, may be even more dependent on adequate scientific information, such as levels of arsenic or fluoride, or the extent of pollution plumes.

Governance may also depend crucially on expanding networks of knowledge and care, to improve mutual understanding of problems and potential solutions, strengthening concern about what happens to other humans and to the environment, and creating trust and capacity to negotiate and craft appropriate agreements, rules, and other institutions. This may also work through the nested structure of institutions, as for example where outside pressures, including from international agreements, lead groundwater users to take action to control groundwater extraction (De Stefano et al. 2018). At the local level, the contextual conditions affecting groundwater governance are complex, in terms of hydrogeology as well as socio-economy. In contrast to surface water, groundwater is often invisible, and often much harder to understand due to the complexity of aquifers and underground flows. Local knowledge, such as about wells and landscape changes, can contribute to understanding changes over time and current conditions, as can technical tools for providing information to support decisions. The experience of the Advanced Center for Water resources Development and Management in India offers an example of combining local and external knowledge in democratic processes to improve governance of groundwater, springs, and other water resources (Aslekar, Joshi, and Kulkarni 2022).

A key challenge is to find ways to move ahead based on available information, rather than being paralyzed by the challenges of trying to gather and analyze comprehensive data. Such efforts can benefit from relevant experience elsewhere, and an adaptive management approach designed to consider and adjust in response to new information as it becomes available.

Research on socio-hydrogeology has called for increased attention to ways of combining knowledge (Re et al. 2021). The Transformations to Sustainable Groundwater Systems Project has supported shared learning across case studies to look at grassroots initiatives in groundwater governance, including insights from ethnography and hydrogeology (Zwarteveen et al. 2021). Processes of learning and discussion about improving groundwater governance may not only consider regulations, financial incentives, and other options for changing institutions but also more fundamentally reshape ideas about sharing identity and relationship to an aquifer, landscape, or territory, and the values and futures that could or should be pursued (Petit et al. 2021)

In devising ways to cope with new challenges, people often draw on and modify their existing knowledge and practices. This kind of improvisation, trying out different modifications and reworkings of existing institutions, has been described and analyzed as institutional bricolage (Cleaver 2012), tinkering (Zwarteveen et al. 2021), or community experimentation (Saidani et al. 2023). The ways in which people share water, within communities and with outsiders, such as pastoralists, may be contingent on multiple criteria and relationships, rather than relying strict boundaries or other criteria that might be applied by external efforts to design institutions (Cleaver and Franks 2003). Even when outside rules are formally established, people may continue to use the same informal rules, or they may modify and negotiate between formal rules and existing practices and concepts (Bruns 2013). In response to droughts in the western United States, farmers and irrigation organizations often pragmatically prefer arrangements to provide some water to all farmers, rather than strictly applying formal legal “prior appropriation” rules (“first in time, first in right”) that would cut off all water to those with more “junior” rights (Hall 2002; MacKinnon 2022). Thus, rather than rigidly or uncreatively applying rules or other institutional tools, people are more likely to use their knowledge and rework rules and practices, applying institutions in improvisational ways. Facilitators can support a creative process of combining and modifying existing and new institutional arrangements (Merrey and Cook 2012).

Learning from examples, stories, scenarios, and narratives

If groundwater governance is something done together by many people, then they can draw on their experience, knowledge, and ideas from many sources. Combining and crafting institutions to achieve mutual gains can benefit from the ways people typically learn and shape their thoughts and actions. This includes learning from examples, stories, scenarios, narratives, and experiments. Such an approach is already reflected in much of the literature on groundwater governance, which examines particular cases to try to understand what happened and draw lessons. Examples suggest possibilities, what was feasible under at least some conditions. Stories center the actions of people, in conflict and cooperation, learning and adapting. And stories are how people can learn about and remember complex contexts with their particular configurations of social and ecological conditions. Scenarios offer structures for exploring futures and using models to understand how systems may change (Schwartz 1991; Scheren et al. 2021; Bellwood-Howard et al. 2022). Narratives link stories with a larger themes such as progress, looming threats (such as climate change), contestation, restoring harmony, protecting local autonomy, or the pursuit of solutions. Water governance narratives may simplify, mystify, obscure, or inspire impossible aspirations, but they may also act as "boundary objects," concepts that provide a basis for conversation among those with different perspectives to discuss what may or may not be possible and what is worth pursuing (Molle 2008). The way these narratives are crafted can shape mindsets about what is possible, and what motivates people. For example, emphasis on various forms of payments and economic incentives may convey that these are the only important motivations, whereas stories about communities caring for groundwater highlight other possible motivations for action. So, examples, stories, scenarios, and narratives are important tools for considering and crafting institutions, for thinking about: "what if ….", "what kind of future do we want," and "what kind of future could we make?"

6. GOVERNING FOR NEXUS GAINS

The complexities of groundwater governance are amplified when we consider how groundwater interacts with the water-energy-food-ecosystems nexus. In this section we illustrate the governance implications of some of these linkages.

Transitions to solar-powered irrigation

As discussed earlier, the potential of solar power for irrigation has attracted much attention and some controversy (Shah et al. 2018; Meera et al. 2018; Verma, Durga, and Shah 2018; Lefore, Closas, and Schmitter 2021). Solar energy for pumping may help farmers obtain more water and earn more income, and benefits could be more widely distributed if solar irrigation is introduced with technologies, finance, and other arrangements to facilitate equitable access. Using solar power instead of diesel or grid electricity from fossil fuels can reduce greenhouse gas emissions. However, the availability of energy with zero marginal cost may also increase groundwater withdrawals, accelerating depletion where withdrawals exceed recharge. Enabling farmers to sell solar power to the grid may provide an alternative incentive that would encourage farmers to pump less (Shah et al. 2018). However, even if this is successfully scaled up, it is unclear whether or where this alone would be sufficient; it appears likely that in many places additional changes may be needed to stop or reverse depletion. So, in terms of creating a toolkit for a specific context in pilot sites, and for this WEFE nexus, a key question is: What combinations of tools could feasibly create transitions to just and sustainable solar-powered irrigation? This includes different geographies: more or less arid or humid, hardrock, alluvial, and other aquifers; and different levels of access to markets for high value crops, as well as different structures of political economy.

Governing recharge and buffer storage in aquifers

Groundwater irrigation can help buffer the impact of variable rainfall, and this may become even more important where climate change leads to more extremes of drought and more intense storms, as well as temperatures that increase crop demands for water (Van Steenbergen and Tuinhof 2009). Keeping some groundwater in reserve for times of drought may result from better governance that can influence how and when water is extracted. Groundwater storage may be much cheaper and better than building new surface storage. Whether and how such interventions are implemented, and how their benefits and costs are distributed depends on how water moves underground, and also, crucially, on governance.

Watershed conservation activities have, under some conditions, contributed to recharging aquifers, which can make more water available for dry season use (Richard-Ferroudji, Raghunath, and Venkatasubramanian 2018). Managed aquifer recharge projects which spread water for infiltration or use injection wells can also be effective in supplying water to aquifers. However, the results of recharge also depend on who gets to use the water, i.e., governance. If water is added with no restrictions on pumping, then it may be easily depleted and not available during times of shortage.

Under favorable conditions, with abundant monsoon rainfall and easily recharged alluvial aquifers, intensive pumping can create additional aquifer storage capacity, and help make water available to support increased agricultural production, as with the Ganga or Bengal “water machines” (Shamsudduha et al. 2022; Mukherji 2022b). In this case, increases in groundwater extraction may be sufficient to increase storage without collective action for governance. However, in areas with less rainfall, less storage capacity, or where rainwater infiltration is more difficult, if large investments are made to recharge aquifers, then it becomes more important to consider who will maintain these water harvesting structures, who will benefit, when and how recharged water will be used, potential impacts on downstream areas, and how institutions might be combined and crafted for better outcomes.

In some cases, just adding supply may be sufficient. However, in other cases, governance could help ensure that some level of storage is reserved for times and need, rather than a first-come-first-served situation where resources are depleted before drought arrives. A key question for this nexus concerns whether, when and when governance may be able to play a role in improving the benefits from aquifer recharge and storage.

Including ecosystems in groundwater governance

Groundwater irrigation has often dried up landscapes, reducing flows to springs, ponds, wetlands, and rivers and reducing the productivity and biodiversity of groundwater-dependent ecosystems (GDES) (Saito et al. 2021; Eamus et al. 2016). Springs, seeps, and other groundwater outflows may be highly sensitive to increased extraction from aquifers (Kreamer, Stevens, and Ledbetter 2015). Wetlands are particularly dependent on high water tables, and even lowering of water tables a few meters may drain wetlands, damaging or destroying their biodiversity and environmental functions.

Although linkages between groundwater governance and ecosystems have often not received much attention, there are relevant experiences and ideas. Watershed conservation activities are often intended to help increase aquifer recharge and in some cases do help restore flows and ecosystems. Irrigation for paddy rice, including pumping of groundwater to irrigate rice, inherently reshapes water flows and ecosystems, shifting the times and places where water is available with ecological consequences. Attempts to increase water productivity, including shifts to sprinkler and drip irrigation, and attempts to reduce methane emissions from rice fields by using alternative approaches to irrigation and rice cultivation, such as shifting to alternate-wet-dry irrigation, aerobic rice, or System of Rice Intensification (Allen and Sander 2019; Takahashi 2023; Datta, Ullah, and Ferdous 2017), may reduce groundwater recharge, with impacts on ecosystems. These relationships point to the importance of the nexus between groundwater irrigation and ecosystems, and the potential for better monitoring, understanding, and management of these relationships across landscapes and waterscapes.

The time lags involved in groundwater flows mean that by the time impacts show up in groundwater-dependent ecosystems it may be too late to prevent damage (Saito et al. 2021). Monitoring at intermediate locations offer a more timely way to detect trends and perhaps prevent problems. Experience with monitoring biodiversity in reforestation of terrestrial habitats, may offer useful lessons for monitoring, understanding, and acting on impacts on GDES. Critical analysis of irrigation efficiency has pointed to the importance of focusing on how surface and underground return flows of irrigation water change, along with actual decreases or increases in beneficial and non-beneficial crop water consumption, evapotranspiration (Perry 2007; Grafton et al. 2018). Therefore, return flows from irrigation can be part of a key linkage between irrigation and GDES. At a broader level, procedures for estimating environmental flows and remote sensing to observe GDES can provide important indicators of the current situations, threats and opportunities. The linkages to ecosystems raise the question of what tools can help groundwater governance contribute to ecosystem protection and restoration?

7. CONCLUSIONS

While there is a wealth of tools apparently available for groundwater governance, there is a dearth of examples of successfully achieving goals such as preventing, halting, or reversing aquifer depletion; actively and equitably managing groundwater storage; or conjunctively managing groundwater irrigation together with ecosystems. There are no institutional panaceas. In many contexts, conventional tools such as licensing wells, metering withdrawals, and setting quotas to limit use of irrigation water are hard to apply, ineffective, or even counterproductive. The effectiveness of such tools may depend on who is involved in decisions, where and when institutional tools are used, and how they are adapted to fit contexts and effectively achieve gains from governance.

The idea of a “toolbox” can direct attention to the range of possible tools that may be combined and crafted into toolkits customized to address problems in particular contexts. Institutional tools may provide information, regulate behavior, influence incentives, or directly provide goods and services. Tools may also enable, require, or influence procedures, such as participatory groundwater games or multistakeholder consultation processes. Typically, tools are layered onto combinations of existing institutions that already govern relationships between humans and water. This makes it crucial to understand the conditions that influence how tools function, including aquifers, farming systems and agricultural markets, existing forms of water tenure, and current governance structures, including the distribution of power, in its various forms.

Games and other experiential tools for social learning can improve understanding and capacity to coordinate cropping choices and water consumption. Aquifer governance can gain from combining local knowledge and collective action with scientific knowledge and external authority that supports local institutions. Institutional design principles offer useful questions to ask about how to organize governance and assess potential changes in rules. Stories and conversations help people learn from experience and consider ways to make changes.

Groundwater governance institutions need to be crafted so they can address the synergies and tradeoffs involved in trying to reduce or reverse groundwater depletion while also pursuing other goals. Better groundwater governance could contribute to equitable and productive use of solar-powered pumping; deliberate management of aquifer storage to buffer variable rainfall, including climate change impacts; and flows that sustain or restore ecosystems.

Efforts to improve groundwater governance can gain by starting from understanding what is already there, in terms of existing institutions, knowledge, and care. Combining local and scientific knowledge can clarify problems and options, as can conversations that consider multiple values of water at local and wider scales. Choices in combining and crafting institutions involve not just technical and economic feasibility but also the politics of deciding what kind of futures to pursue and how to do so, who has a say in making those decisions, and constructing coalitions to enact and implement changes in governance.

REFERENCES

Aarnoudse, Eefje, and Bettina Bluemling. 2017. "Controlling Groundwater through Smart Card Machines: The Case of Water Quotas and Pricing Mechanisms in Gansu Province, China." Groundwater Solutions Initiative for Policy and Practice (GRIPP) Case Profile Series 2. Sri Lanka: International Water Management Institute. https://doi.org/10.5337/2016.224.

Aarnoudse, Eefje, Wei Qu, Bettina Bluemling, and Thomas Herzfeld. 2017. "Groundwater Quota versus Tiered Groundwater Pricing: Two Cases of Groundwater Management in North-West China." *International Journal of Water Resources Development* 33 (6): 917–34. https://doi.org/10.1080/07900627.2016.1240069.

ADB, (Asian Development Bank). 2000. "Project Completion Report on the Left Bank Outfall Drain Project in Pakistan (Stage I) (Loan 700-PAK[SF])." Project Completion Report PAK 17055. Manila, Philippines: Asian Development Bank.

Allen, Justin, and Bjoern Ole Sander. 2019. "The Diverse Benefits of Alternate Wetting and Drying (AWD)."

Aslekar, Uma, Dhaval Joshi, and Himanshu Kulkarni. 2022. "What Are We Allocating and Who Decides? Democratising Understanding of Groundwater and Decisions for Judicious Allocations in India."

Ayres, Andrew B., Eric C. Edwards, and Gary D. Libecap. 2018. "How Transaction Costs Obstruct Collective Action: The Case of California's Groundwater." *Journal of Environmental Economics and Management* 91: 46–65.

Bellwood-Howard, Imogen, John Thompson, Mohammad Shamsudduha, Richard G. Taylor, Devotha B. Mosha, Gebrehaweria Gebrezgi, Andrew K. P. R. Tarimo, Japhet J. Kashaigili, Yahaya Nazoumou, and Ouassa Tiékoura. 2022. "A Multicriteria Analysis of Groundwater Development Pathways in Three River Basins in Sub-Saharan Africa." *Environmental Science & Policy* 138 (December): 26–43. https://doi.org/10.1016/j.envsci.2022.09.010.

Birner, Regina, S. Gupta, and N. Sharma. 2011. "The Political Economy of Agricultural Policy Reform in India: Fertilizers and Electricity for Irrigation." Research Report 174. Washington D.C.: International Food Policy Research Institute.

Blomquist, William. 1992. *Dividing the Waters: Governing Groundwater in Southern California*. San Francisco: Institute for Contemporary Studies.

Bruns, Bryan. 2013. "Bureaucratic Bricolage and Adaptive Co-Management in Indonesian Irrigation." In *The Social Life of Water*, edited by John R. Wagner, 255–77. New York, NY, USA: Berghan Books.

Bruns, Bryan, and Ruth Meinzen-Dick, eds. 2000. *Negotiating Water Rights*. New Delhi, India: Vistaar.

———. 2001. "Water Rights and Legal Pluralism: Four Contexts for Negotiation." *Natural Resources Forum* 25 (1): 1–10.

Bruns, Bryan, Claudia Ringler, and Ruth Meinzen-Dick. 2005. "Reforming Water Rights: Governance, Tenure, and Transfers." In *Water Rights Reform: Lessons for Institutional Design*, edited by Bryan Bruns, Claudia Ringer, and Ruth Meinzen-Dick. Washington, D.C.: IFPRI.

CGIAR. 2021. "NEXUS Gains." CGIAR Research Initiatives. 2021. https://www.cgiar.org/initiative/28-nexus-gains-realizing-multiple-benefits-across-water-energy-food-forest-biodiversity-systems/.

Cleaver, Frances. 2012. *Development through Bricolage: Rethinking Institutions for Natural Resource Management*. 1st ed. London, UK: Routledge.

Cleaver, Frances, and Tom Franks. 2003. "How Institutions Elude Design: River Basin Management and Sustainable Livelihoods." *Presented at The Alternative Water Forum*.

Cole, Daniel H., and Peter Z. Grossman. 2010. "Institutions Matter! Why the Herder Problem Is Not a Prisoner's Dilemma." *Theory and Decision* 69 (2): 219–31.

Cox, Michael, Gwen Arnold, and Sergio Villamayor-Tomas. 2010. "A Review of Design Principles for Community-Based Natural Resource Management." *Ecology & Society* 15 (4). https://doi.org/10.5751/es-03704-150438.

Datta, Avishek, Hayat Ullah, and Zannatul Ferdous. 2017. "Water Management in Rice." In *Rice Production Worldwide*, edited by Bhagirath S. Chauhan, Khawar Jabran, and Gulshan Mahajan, 255–77. Cham: Springer International Publishing. https://doi.org/10.1007/978-3-319-47516-5_11.

David, Paul A. 1985. "Clio and the Economics of QWERTY." *The American Economic Review* 75 (2): 332–37.

De Stefano, Lucia, Christina Welch, Julia Urquijo, and Dustin Garrick. 2018. "Groundwater Governance in the Rio Grande: Co-Evolution of Local and Intergovernmental Management."

Dillon, Peter, Yan Zheng, William Alley, and Joanne Vanderzalm, eds. 2022. *Managed Aquifer Recharge: Overview and Governance*. IAH Special Publication. https://recharge.iah.org/.

Eamus, Derek, Baihua Fu, Abraham E. Springer, and Lawrence E. Stevens. 2016. "Groundwater Dependent Ecosystems: Classification, Identification Techniques and Threats." In *Integrated Groundwater Management: Concepts, Approaches and Challenges*, edited by Anthony J. Jakeman, Olivier Barreteau, Randall J. Hunt, Jean-Daniel Rinaudo, and Andrew Ross, 313–46. Springer.

Edmunds, David, and Eva Wollenberg. 2001. "A Strategic Approach to Multi-Stakeholder Negotiations." *Development and Change* 32 (231–253).

ElDidi, Hagar, Shivanyaa Rawat, Ruth Suseela Meinzen-Dick, and Rahul Chaturvedi. 2021. "Polycentricity and Multi-Stakeholder Platforms: Governance of the Commons in India." Intl Food Policy Res Inst. https://doi.org/10.2499/p15738coll2.134845.

Esteban, Encarna, and José Albiac. 2012. "The Problem of Sustainable Groundwater Management: The Case of La Mancha Aquifers, Spain." *Hydrogeology Journal* 20 (5): 851–63.

Falk, Thomas, W. Zhang, Ruth Meinzen-Dick, R. Sanil, P. Priyadarshi, I. Soliev, and L. Bartels. Forthcoming. "Games for Experiential Learning: Triggering Collective Changes in Commons Management." *Ecology and Society*.

FAO. 2020. *Unpacking Water Tenure for Improved Food Security and Sustainable Development*. FAO Land and Water Discussion Papers 15. Rome, Italy: FAO. https://doi.org/10.4060/cb1230en.

FES. 2022. "Composite Landscape Assessment & Restoration Tool (CLART)." India Observatory. 2022. https://www.indiaobservatory.org.in/tool/clart.

FES, (Foundation for Ecological Security), (International Food Policy Research Institute) IFPRI, and (International Crop Research Institute for the Semi-Arid Tropics) ICRISAT. 2021. “Commoning the Commons: A Sourcebook to Strengthen Management and Governance of Water as Commons.” Sourcebook. Gujarat, India: Foundation for Ecological Security. https://fes.org.in/resources/sourcebooks,manuals,atlases-&-ecoprofiles/sourcebooks/strengthening_governance_and_management_of_water_as_commons_May_2022.pdf.

Frantz, Christopher K., and Saba Siddiki. 2021. “Institutional Grammar 2.0: A Specification for Encoding and Analyzing Institutional Design.” *Public Administration* 99 (2): 222–47.

Garduno, Hector. 2005. “Lessons from Implementing Water Rights in Mexico.” In *Water Rights Reform: Lessons for Institutional Design*, edited by Bryan Bruns, Claudia Ringer, and Ruth Meinzen-Dick, 85–112. Washington, D.C.: IFPRI.

Garrick, Dustin. 2016. “Never Waste a Crisis: Drought as an Opportunity to Bring Robust Water-Policy Reform to California.” In *Transformational Change in Environmental and Natural Resource Management*, 109–22. Routledge.

Global Groundwater Statement. 2019. “Global Groundwater Sustainability: A Call to Action.” 2019. https://www.groundwaterstatement.org/.

Grafton, R. Q., J. Williams, C. J. Perry, Francois Molle, C. Ringler, P. Steduto, B. Udall, et al. 2018. “The Paradox of Irrigation Efficiency.” *Science* 361 (6404): 748–50. https://doi.org/10.1126/science.aat9314.

Hall, G. Emlen. 2002. *High and Dry: The Texas-New Mexico Struggle for the Pecos River*. Albuquerque: University of New Mexico Press.

Hodgson, S. 2016. “Exploring the Concept of Water Tenure.” Land and Water Discussion Paper 10. Rome: FAO. http://www.fao.org/3/a-i5435e.pdf.

Howlett, Michael. 2019. *Designing Public Policies: Principles and Instruments*. Routledge.

Huggins, Xander, Tom Gleeson, Juan Castilla-Rho, Cameron Holley, Viviana Re, and James S. Famiglietti. 2022. “Groundwater Connections and Sustainability in Social-Ecological Systems.” *Preprint*, April. https://eartharxiv.org/repository/view/3248/.

Hussain, Mohammed S., Hany F. Abd-Elhamid, Akbar A. Javadi, and Mohsen M. Sherif. 2019. “Management of Seawater Intrusion in Coastal Aquifers: A Review.” *Water* 11 (12): 2467. https://doi.org/10.3390/w11122467.

IGRAC, (International Groundwater Resources Assessment Centre). 2018. “Groundwater Overview: Making the Invisible Visible.” Geneva, Switzerland: UN Water. https://www.unwater.org/sites/default/files/app/uploads/2018/09/Groundwater-overview-Making-the-invisible-visible_Print.pdf.

Jarvis, W. Todd. 2011. “Unitization: A Lesson in Collective Action from the Oil Industry for Aquifer Governance.” *Water International* 36 (5): 619–30.

Kinzelbach, Wolfgang, Haijing Wang, Yu Li, Lu Wang, and Ning Li. 2022. *Groundwater Overexploitation in the North China Plain: A Path to Sustainability*. Springer Nature. https://link.springer.com/content/pdf/10.1007/978-981-16-5843-3.pdf?pdf=button.

Kosec, Katrina, and Danielle Resnick. 2019. “Governance: Making Institutions Work for Rural Revitalization.” In *2019 Global Food Policy Report*, edited by International Food Policy Research Institute, 68–77. Washington D.C.: International Food Policy Research Institute (IFPRI). https://econpapers.repec.org/scripts/redir.pf?u=https%3A%2F%2Fwww.ifpri.org%2Fcdmref%2Fp15738coll2%2Fid%2F133138%2Ffilename%2F133344.pdf;h=repec:fpr:ifpric:9780896293502-08.

Kreamer, David K., Lawrence E. Stevens, and Jeri D. Ledbetter. 2015. “Groundwater Dependent Ecosystems—Science, Challenges, and Policy Directions.” *Groundwater* 205: 230.

Lefore, Nicole, Alvar Closas, and Petra Schmitter. 2021. “Solar for All: A Framework to Deliver Inclusive and Environmentally Sustainable Solar Irrigation for Smallholder Agriculture.” *Energy Policy* 154: 112313.

Levi, Margaret. 1989. *Of Rule and Revenue*. University of California Pr.

Lipsey, R. G., and Kelvin Lancaster. 1956. “The General Theory of Second Best.” *The Review of Economic Studies* 24 (1): 11–32.

Loos, Jonathon, Krister Andersson, Shauna Bulger, Michael Cox, Alexander Gebben, and Steven M. Smith. 2022. “Individual to Collective Adaptation through Incremental Change in Colorado Groundwater Governance.” *Frontiers in Environmental Science*, 10:958597. https://doi.org/doi: 10.3389/fenvs.2022.958597.

MacKinnon, Anne. 2022. “Public Waters: Lessons from Wyoming for the American West.” Oxford University Press.

Meera, Sahasranaman, M. D. Kumar, Bassi Nitin, Singh Mahendra, and Ganguly Arijit. 2018. “Solar Irrigation Cooperatives-Creating the Frankenstein’s Monster for India’s Groundwater.” *Economic and Political Weekly* 53 (21).

Meinzen-Dick, R., L. Nkonya, Barbara Van Koppen, Mark Giordano, and John Butterworth. 2007. “Understanding Legal Pluralism in Water and Land Rights: Lessons from Africa and Asia.” *Community-Based Water Law and Water Resource Management Reform in Developing Countries*, 12–27.

Meinzen-Dick, Ruth. 1996. “Groundwater Markets in Pakistan: Participation and Productivity.” Research Report 105. Washington D.C.: International Food Policy Research Institute. http://www.ifpri.org/pubs/abstract/abstr105.htm.

———. 2000. “Public, Private, and Shared Water: Groundwater Markets and Access in Pakistan.” In *Negotiating Water Rights*, edited by Bryan Bruns and Ruth Meinzen-Dick, 245–63. New Delhi, India: Vistaar.

———. 2007. “Beyond Panaceas in Water Institutions.” *Publications of the National Academy of Sciences* 104 (39): 15200–205. https://doi.org/10.1073/pnas.0702296104.

———. 2014. “Property Rights and Sustainable Irrigation: A Developing Country Perspective.” *Agricultural Water Management* 145: 23–31.

Meinzen-Dick, Ruth, Rahul Chaturvedi, Laia Domènech, Rucha Ghate, Marco Janssen, Nathan Rollins, and K. Sandeep. 2016. “Games for Groundwater Governance: Field Experiments in Andhra Pradesh, India.” *Ecology and Society* 21 (3). https://doi.org/10.5751/ES-08416-210338.

Meinzen-Dick, Ruth, Marco Janssen, S. Kandikuppa, R. Chaturvedi, K. Rao, and S. Theis. 2018. "Playing Games to Save Water: Collective Action Games for Groundwater Management in Andhra Pradesh, India." *World Development* 107 (July): 40–53. https://doi.org/10.1016/j.worlddev.2018.02.006.

Merrey, Douglas, and S. Cook. 2012. "Fostering Institutional Creativity at Multiple Levels: Towards Facilitated Institutional Bricolage." *Water Alternatives* 5 (1): 1–19. https://www.water-alternatives.org/index.php/volume5/v5issue1/154-a5-1-1.

Molle, Francois. 2008. "Nirvana Concepts, Narratives and Policy Models: Insights from the Water Sector." *Water Alternatives* 1 (1): 131–56. https://www.water-alternatives.org/index.php/volume1/v1issue1/20-a-1-1-8.

Molle, Francois, and Alvar Closas. 2016. "Groundwater Governance: A Synthesis." Project Report 6. Groundwater Governance in the Arab World–Taking Stock and Addressing the Challenges. Sri Lanka: International Water Management Institute. https://publications.iwmi.org/pdf/H048392.pdf.

———. 2020a. "Comanagement of Groundwater: A Review." *Wiley Interdisciplinary Reviews: Water* 7 (1): e1394.

———. 2020b. "Why Is State-Centered Groundwater Governance Largely Ineffective? A Review." *Wiley Interdisciplinary Reviews: Water* 7 (1): e1395. https://doi.org/10.1002/wat2.1395.

———. 2020c. "Groundwater Licensing and Its Challenges." *Hydrogeology Journal*, May. https://doi.org/10.1007/s10040-020-02179-x.

———. 2021. "Groundwater Metering: Revisiting a Ubiquitous 'Best Practice.'" *Hydrogeology Journal* 29 (5): 1857–70.

Molle, Francois, Elena López-Gunn, and Frank Van Steenbergen. 2018. "The Local and National Politics of Groundwater Overexploitation." *Water Alternatives* 11 (3).

Mukherji, Aditi. 2006. "Political Ecology of Groundwater: The Contrasting Case of Water-Abundant West Bengal and Water-Scarce Gujarat, India." *Hydrogeology Journal* 14 (3): 392–406.

———. 2022a. "Sustainable Groundwater Management in India Needs a Water-Energy-Food Nexus Approach." *Applied Economic Perspectives and Policy* 44 (1): 394–410.

———. 2022b. "The 'Water Machine' of Bengal." *Science* 377 (6612): 1258–59.

Mukherji, Aditi, and Tushaar Shah. 2005. "Groundwater Socio-Ecology and Governance: A Review of Institutions and Policies in Selected Countries." *Hydrogeology Journal* 13 (1): 328–45.

National Research Council. 1986. *Proceedings of the Conference on Common Property Resource Management, April 21-26, 1985*. National Academies.

North, Douglass C. 1990. *Institutions, Institutional Change and Economic Performance*. New York: Cambridge University Press.

Ostrom, Elinor. 1965. "Public Entrepreneurship: A Case Study in Ground Water Basin Management." Ph.D. Dissertation, Los Angeles: University of California, Los Angeles.

———. 1990. *Governing the Commons: The Evolution of Institutions for Collective Action*. Cambridge, UK: Cambridge University Press.

———. 2000. "Collective Action and the Evolution of Social Norms." *Journal of Economic Perspectives* 14 (3): 137–58.

———. 2005. *Understanding Institutional Diversity*. Princeton, NJ, USA: Princeton University Press.

Ostrom, Elinor, Thomas Dietz, Nives Dolsak, Paul C Stern, Susan Stonich, and Elke U Weber. 2002. *The Drama of the Commons*. Washington, D.C.: National Academies Press.

Ostrom, Elinor, Marco A. Janssen, and John M. Anderies. 2007. "Introduction: Going Beyond Panaceas." *Proceedings of the National Academy of Sciences* 104 (39): 15176–78.

Perry, Chris. 2007. "Efficient Irrigation; Inefficient Communication; Flawed Recommendations." *Irrigation and Drainage* 56 (4): 367–78. https://doi.org/10.1002/ird.323.

Petit, Olivier, Aurélien Dumont, Stéphanie Leyronas, Quentin Ballin, Sami Bouarfa, Nicolas Faysse, Marcel Kuper, François Molle, Charlotte Alcazar, and Emmanuel Durand. 2021. "Learning from the Past to Build the Future Governance of Groundwater Use in Agriculture." *Water International* 46 (7–8): 1037–59.

Re, Viviana, Myat Mon Thin, Chiara Tringali, Mya Mya, Enrico Destefanis, and Elisa Sacchi. 2021. "Laying the Groundwork for Raising Awareness on Water Related Issues with a Socio-Hydrogeological Approach: The Inle Lake Case Study (Southern Shan State, Myanmar)." *Water* 13 (17): 2434. https://doi.org/10.3390/w13172434.

Reddy, V. Ratna, Paul Pavelic, and M. Srinivasa Reddy. 2021. "Participatory Management and Sustainable Use of Groundwater: A Review of the Andhra Pradesh Farmer-Managed Groundwater Systems Project in India." 5. GRIPP Case Profile Series. Sri Lanka: International Water Management Institute. https://gripp.iwmi.org/2021/12/16/gripp-case-profile-series-issue-5/.

Repetto, Robert, ed. 2006. *Punctuated Equilibrium and the Dynamics of U.S. Environmental Policy*. New Haven: Yale University Press.

Richard-Ferroudji, Audrey, T. P. Raghunath, and G. Venkatasubramanian. 2018. "Managed Aquifer Recharge in India: Consensual Policy but Controversial Implementation." *Water Alternatives* 11 (3): 749–69.

Saidani, Mohamed Amine, Uma Aslekar, Marcel Kuper, and Jeltsje Kemerink-Seyoum. 2023. "Sharing Difficult Waters: Community-Based Groundwater Recharge and Use in Algeria and India." *Water Alternatives* 16 (1). http://dx.doi.org/10.2499/9780896291720.

Saito, Laurel, Bill Christian, Jennifer Diffley, Holly Richter, Melissa M. Rohde, and Scott A. Morrison. 2021. "Managing Groundwater to Ensure Ecosystem Function." *Groundwater* 59 (3): 322–33.

Scheren, Peter, Peter Tyrrell, Peadar Brehony, James R. Allan, Jessica PR Thorn, Tendai Chinho, Yemi Katerere, Vanessa Ushie, and Jeffrey S. Worden. 2021. "Defining Pathways towards African Ecological Futures." *Sustainability* 13 (16): 8894.

Schlager, Edella. 2005. "Getting the Relationships Right in Water Property Rights." In *Water Rights Reform: Lessons for Institutional Design*, edited by Bryan Bruns, Claudia Ringler, and Ruth Meinzen-Dick, 27–54. Washington, D.C.: IFPRI.

Schlager, Edella, William Blomquist, and Shui Yan Tang. 1994. "Mobile Flows, Storage and Self-Organized Institutions for Governing Common-Pool Resources." *Land Economics* 70 (3): 294–317.

Schreiner, Barbara, and Barbara Van Koppen. 2018. "Establishing Hybrid Water User Rights Systems in Sub-Saharan Africa: A Practical Guide for Managers." Colombo, Sri Lanka: Pegasys Institute and IWMI.

Schwartz, Peter. 1991. *The Art of the Long View*. New York: Doubleday.

Shah, Tushaar. 2000. "Mobilising Social Energy against Environmental Challenge: Understanding the Groundwater Recharge Movement in Western India." In *Natural Resources Forum*, 24:197–209. Wiley Online Library.

———. 2009. *Taming the Anarchy: Groundwater Governance in South Asia*. Washington, DC: RFF Press.

Shah, Tushaar, Abhishek Rajan, Gyan Prakash Rai, Shilp Verma, and Neha Durga. 2018. "Solar Pumps and South Asia's Energy-Groundwater Nexus: Exploring Implications and Reimagining Its Future." *Environmental Research Letters* 13 (11): 115003. https://doi.org/10.1088/1748-9326/aae53f.

Shamsudduha, Mohammad, Richard G. Taylor, Md Izazul Haq, Sara Nowreen, Anwar Zahid, and Kazi Matin Uddin Ahmed. 2022. "The Bengal Water Machine: Quantified Freshwater Capture in Bangladesh." *Science* 377 (6612): 1315–19.

Steenbergen, F., A. Tuinhof, and others. 2010. "Managing the Water Buffer for Development and Climate Change Adaptation: Groundwater Recharge, Retention, Reuse and Rainwater Storage."

Steins, Nathalie A., and Victoria M. Edwards. 1998. "Platforms for Collective Action in Multiple-Use CPRs." *Maritime Anthropological Studies* 4: 17–39.

Taher, Taha, Bruns, Bryan, Bamaga, Omar, Al-Weshali, Adel, and Frank Van Steenbergen. 2012. "Local Groundwater Governance in Yemen: Building on Traditions and Enabling Communities to Craft New Rules." *Hydrogeology Journal* 20 (6): 1177–88.

Takahashi, Kazushi. 2023. "A UFO? Assessment of System of Rice Intensification from the Agricultural Economics Perspective." In *Agricultural Development in Asia and Africa*, 87–97. Springer, Singapore.

Theesfeld, Insa. 2010. "Institutional Challenges for National Groundwater Governance: Policies and Issues." *Groundwater* 48 (1): 131–42. https://doi.org/10.1111/j.1745-6584.2009.00624.x.

Uhlenbrook, Stefan, and Claudia Ringler. 2021. "An Integrated Approach to Realize Multiple Benefits across Water, Energy, Food, Forests and Biodiversity." IFPRI. https://www.ifpri.org/blog/integrated-approach-realize-multiple-benefits-across-water-energy-food-forests-and-biodiversity.

Uphoff, Norman, and Jeff Langholz. 1998. "Incentives for Avoiding the Tragedy of the Commons." *Environmental Conservation* 25 (3): 251–61.

Van, Frank, and Tushaar Shah. 2003. "Rules Rather than Rights: Self-Regulation in Intensively Used Groundwater Systems." In *Intensive Use of Groundwater: Challenges and Opportunities*, edited by M. Llamas and E. Custodio, 241–56. Lisse, The Netherlands: Balkema. https://hdl.handle.net/10568/37476.

Van Koppen, Barbara. 2022. "Living Customary Water Tenure in Rights-Based Water Management in Sub-Saharan Africa." Research Report 183. Sri Lanka: International Water Management Institute.

Van Rooyen, André F., Peter Ramshaw, Martin Moyo, Richard Stirzaker, and Henning Bjornlund. 2017. "Theory and Application of Agricultural Innovation Platforms for Improved Irrigation Scheme Management in Southern Africa." *International Journal of Water Resources Development* 33 (5): 804–23. https://doi.org/10.1080/07900627.2017.1321530.

Van Steenbergen, Frank, and Albert Tuinhof. 2009. "Managing the Water Buffer for Development and Climate Change Adaptation: Groundwater Recharge, Retention, Reuse and Rainwater Storage." Wageningen, The Netherlands: Wageningen Academic Publishers. https://edepot.wur.nl/11917.

Venkata, S., J. Burke, G. Das, and Land and Water Division. 2013. *Smallholders and Sustainable Wells: A Retrospect: Participatory Groundwater Management in Andhra Pradesh (India)*. Rome, Italy: FAO. https://www.fao.org/documents/card/en/c/f8d7efed-e9b9-55fd-ada3-b806eacab16d/.

Verma, Shilp, Neha Durga, and Tushaar Shah. 2018. "Solar Irrigation Pumps and India's Energy-Irrigation Nexus." IWMI-Tata Water Policy Research Highlight. International Water Management Institute. http://www.iwmi.cgiar.org/iwmi-tata/PDFs/iwmi-tata_water_policy_research_highlight-issue_02_2018.pdf.

Verma, Shilp, Sunderrajan Krishnan, Ankith Reddy V., and K. Rajendra Reddy. 2012. "Andhra Pradesh Farmer Managed Groundwater Systems (APFAMGS): A Reality Check." Water Policy Research Highlight 37. Colombo, Sri Lanka: International Water Management Institute. http://www.iwmi.cgiar.org/iwmi-tata/PDFs/2012_Highlight-37.pdf.

Whaley, Luke. 2018. "The Critical Institutional Analysis and Development (CIAD) Framework." *International Journal of the Commons* 12 (2).

Zheng, Yan, Andrew Ross, Karen G. Villholth, and Peter Dillon. 2021. "Managing Aquifer Recharge. A Showcase for Resilience and Sustainability." *UNESCO, Paris. Retrieved August* 10: 2021.

Zwarteveen, Margreet, Marcel Kuper, Cristian Olmos-Herrera, Muna Dajani, Jeltsje Kemerink-Seyoum, Cleaver Frances, Linnea Beckett, et al. 2021. "Transformations to Groundwater Sustainability: From Individuals and Pumps to Communities and Aquifers." *Current Opinion in Environmental Sustainability* 49 (April): 88–97. https://doi.org/10.1016/j.cosust.2021.03.004.

APPENDIX: SOURCES ABOUT INSTITUTIONAL TOOLS FOR GROUNDWATER GOVERNANCE

General introduction to groundwater governance institutions

- Theesfeld, Insa. 2010. "Institutional Challenges for National Groundwater Governance: Policies and Issues." *Groundwater* 48 (1): 131–42. https://doi.org/10.1111/j.1745-6584.2009.00624.x

Edited volumes on groundwater governance and management

- Villholth, Karen G., E López-Gunn, and K. Conti, eds. 2018. *Advances in Groundwater Governance*. Boca Raton: CRC Press/Balkema. https://www.un-igrac.org/sites/default/files/resources/files/advances-in-groundwater-governance.pdf.
- Jakeman, Anthony J., Olivier Barreteau, Randall J. Hunt, Jean-Daniel Rinaudo, and Andrew Ross. 2016. *Integrated Groundwater Management*. Springer Nature. https://library.oapen.org/bitstream/handle/20.500.12657/28049/1001945.pdf?seque.

Reports from Groundwater Governance - A Global Framework for Action Project (2011-2015)

- https://groundwaterportal.net/project/groundwater-governance-gwg

Comparative assessment of international experience with groundwater governance

- Molle, Francois, and Alvar Closas. 2016. "Groundwater Governance: A Synthesis." Project Report 6. Groundwater Governance in the Arab World–Taking Stock and Addressing the Challenges. Sri Lanka: International Water Management Institute. https://publications.iwmi.org/pdf/H048392.pdf
    - Includes: Controlling the number and expansion of wells: regularizing existing wells, exemptions, licensing and water-use entitlements, licenses for altering wells, zoning and special management zones, buyback of wells and licenses, canceling licenses and backfilling illegal wells, controlling drillers, indirect regulation tools.
    - Controlling abstraction by existing wells: metering, pricing policies, quotas and reduction of entitlements, technology fixes to reduce groundwater use, temporary retirement of irrigated land, indirect regulation tools.
    - Supply augmentation options: transfers or storage of surface water, managed aquifer recharge, desalination. Trading in groundwater licenses/rights.
- ———. 2009. "Water Scarcity, Prices and Quotas: A Review of Evidence on Irrigation Volumetric Pricing." *Irrigation and Drainage Systems* 23 (1): 43–58.
- ———. 2020. "Groundwater Licensing and Its Challenges." *Hydrogeology Journal* 28 (6): 1961–74.
- ———. 2021. "Groundwater Metering: Revisiting a Ubiquitous 'Best Practice.'" *Hydrogeology Journal* 29 (5): 1857–70.
- ———. 2020. "Why Is State-Centered Groundwater Governance Largely Ineffective? A Review." *Wiley Interdisciplinary Reviews: Water* 7 (1): e1395. https://doi.org/10.1002/wat2.1395.
- ———.. 2020. "Comanagement of Groundwater: A Review." *Wiley Interdisciplinary Reviews: Water* 7 (1): e1394.

Groundwater game practitioner's manual 2.0. and explanation of using the groundwater game

- https://gamesforsustainability.org/practitioners/#groundwater-game
- Commoning the Commons: A Sourcebook to Strengthen Management and Governance of Water as Commons. Foundation for Ecological Security, International Crops Research Institute for the Semi-Arid Tropics, and International Food Policy Research Institute. 2021. https://fes.org.in/resources/sourcebooks,manuals,atlases-&-ecoprofiles/manuals/strengthening_governance_and_management_of_water_as_commons.pdf

Apps for groundwater monitoring, crop-water budgeting, and geographic information system to support decisions for soil and water conservation

- https://www.indiaobservatory.org.in/our-tools
- Crop Water Budgeting Portal https://cwb.fes.org.in/
- Groundwater Monitoring Tool https://www.indiaobservatory.org.in/tool/gmt

Games

- Groundwater game for social learning, developed by FES and IFPRI
    - https://gamesforsustainability.org/practitioners/#groundwater-game
- Game for social learning on collective water harvesting, developed by FES and ICRISAT
    - https://gamesforsustainability.org/practitioners/#game-on-managing-check-dams
- Save the water game used in the research in China by Kinzelbach et al.
    - https://savethewater-game.com/game/

Analysis of Chinese experience with groundwater management tools and recommended measures

- Kinzelbach, Wolfgang, Haijing Wang, Yu Li, Lu Wang, and Ning Li. 2022. *Groundwater Overexploitation in the North China Plain: A Path to Sustainability*. Springer Nature. https://link.springer.com/content/pdf/10.1007/978-981-16-5843-3.pdf?pdf=button.
    - Includes: Policy options of over-pumping control in the North China Plain: permit policy for well drilling, well-spacing policy, quota management, water resources fee and tax, irrigation water price policy, water rights system and water markets.
    - Groundwater over-pumping control measures in Hebei Province: seasonal land fallowing, substitution of non-food crops for grain crops, replacing groundwater by surface water, buy-back of water rights, "increase price and provide subsidy", tiered scheme of water fees, import of surface water versus water saving, change of cropping structure.

An information-based approach to groundwater governance, and some of its limitations

- Venkata, S., J. Burke, G. Das, and Land and Water Division. 2013. Smallholders and Sustainable Wells: A Retrospect: Participatory Groundwater Management in Andhra Pradesh (India). Rome, Italy: FAO. https://www.fao.org/documents/card/en/c/f8d7efed-e9b9-55fd-ada3-b806eacab16d/
- Reddy, V. Ratna, Paul Pavelic, and M. Srinivasa Reddy. 2021. "Participatory Management and Sustainable Use of Groundwater: A Review of the Andhra Pradesh Farmer-Managed Groundwater Systems Project in India." 5. GRIPP Case Profile Series. Sri Lanka: International Water Management Institute. https://gripp.iwmi.org/2021/12/16/gripp-case-profile-series-issue-5/.

Well spacing and other rules for governing groundwater

- Steenbergen, F. van, and Tushaar Shah. 2003. "Rules Rather than Rights: Self-Regulation in Intensively Used Groundwater Systems." In *Intensive Use of Groundwater: Challenges and Opportunities*, edited by M. Llamas and E. Custodio, 241–56. Lisse, The Netherlands: Balkema. https://hdl.handle.net/10568/37476.

Water tenure assessment methodology, potentially applicable for groundwater

- Hodgson, S. 2016. "Exploring the Concept of Water Tenure." Land and Water Discussion Paper 10. Rome: FAO. http://www.fao.org/3/a-i5435e.pdf.
- Water tenure assessment guide. Available by request to Sofia.Espinosa@fao.org
    - https://www.fao.org/in-action/knowat/wt-assessment/methodology/en/

Hybrid water rights systems combining targeted formal licensing and customary tenure

- Schreiner, Barbara, and Barbara Van Koppen. 2018. "Establishing Hybrid Water User Rights Systems in Sub-Saharan Africa: A Practical Guide for Managers." Colombo, Sri Lanka: Pegasys Institute and IWMI. https://publications.iwmi.org/pdf/H048975.pdf

Managed aquifer recharge: There is increasing information available on the technology and economics of managed aquifer recharge, but information on governance is more limited

- Dillon, Peter, Yan Zheng, William Alley, and Joanne Vanderzalm, eds. 2022. *Managed Aquifer Recharge: Overview and Governance*. IAH Special Publication. https://recharge.iah.org/files/2022/06/MAR-overview-and-governance-IAH-Special-Publication-18June2022.pdf
- Richard-Ferroudji, Audrey, T. P. Raghunath, and G. Venkatasubramanian. 2018. "Managed Aquifer Recharge in India: Consensual Policy but Controversial Implementation." *Water Alternatives* 11 (3): 749–69. https://www.water-alternatives.org/index.php/alldoc/articles/vol11/v11issue3/463-a11-3-16/file
- Saidani, Mohamed Amine, Uma Aslekar, Marcel Kuper, and Jeltsje Kemerink-Seyoum. 2023. "Sharing Difficult Waters: Community-Based Groundwater Recharge and Use in Algeria and India." *Water Alternatives* 16 (1). http://dx.doi.org/10.2499/9780896291720.

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