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Review

Modes and Approaches of Groundwater Governance: A Survey of Lessons Learned from Selected Cases across the Globe

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Abstract: The crucial role of groundwater and the centrality of water governance in accommodating growing water demands sustainably are becoming well recognized. We review 10 case studies of groundwater governance—representing diverse global regions and local contexts—from the perspective of four well-established elements: (1) institutional setting; (2) availability and access to information and science; (3) robustness of civil society; and (4) economic and regulatory frameworks. For institutional setting, we find that governing is often a thankless task that paradoxically requires popularity; legislation does not always translate to implementation; conflict resolution is central to governance; and funding is critical for governance. In terms of information access, we see: a need for research for natural systems, social systems, and institutions; trust as an essential element in research; and that urbanized landscapes are critical components of groundwater governance. Looking at civil society robustness, we observe that equity is an essential element for governance; community-based governance requires intention; and leaders can play a powerful role in uniting stakeholders. As for frameworks, the cases suggest that economic incentives sometimes yield unintended results; "indirect" management should be used cautiously; and economic incentives' effectiveness depends on the system employed. Collectively, the lessons speak to the need for shared governance capacities on the part of governments at multiple levels and civil society actors.

Keywords: groundwater governance; water; stakeholder participation; equity; water security; case studies

1. Introduction

Two global programs underscore the value of examining groundwater-governance practices through case study analysis. The Global Environment Facility's (GEF) comprehensive project, "Groundwater Governance—A Global Framework for Action" (2011–2015), aims to raise awareness of the "*paramount importance of groundwater resources and their sustainable management in averting the impending water crisis*" [1]. A parallel global effort to examine water governance (not specifically groundwater), initiated in 2013 by the Organization for Economic Co-operation and Development (OECD), acknowledges that "*managing and securing access to water for all is not only a question of money, but equally a matter of good governance*" [2].

At the core of the GEF et al. (2016) [1] Groundwater Governance project are 12 thematic papers, followed by five continental-scale regional consultations held around the world, and a "Global Groundwater Diagnostic." These steps surveyed groundwater-governance practices and identified relevant opportunities, constraints, and challenges. In this article—which has its origins in GEF-commissioned series' Thematic Paper Number 5, "Groundwater policy and governance" [3]—we revisit the findings of that 2013 report by analyzing five of its most cogent case studies and complementing those sources with five more recent studies.

The objective of this article is—through an analysis of selected case studies—to demonstrate how the modes and approaches of groundwater governance depend on four governance elements: (1) institutional setting; (2) availability and access to information and science; (3) robustness of civil society; and (4) economic and regulatory frameworks.

1.1. Institutional Setting

If we accept a working definition of groundwater governance as "*the overarching framework of groundwater use laws, regulations, and customs, as well as the processes of engaging the public sector, the private sector, and civil society*" (p. 678) [4], the role and influence of institutions is the principal pillar upon which governance rests. The institutional setting of a nation's or a region's groundwater sector comprises the governmental, nongovernmental, and private sector agencies, organizations, and decision-making and managerial practices. A thorough appreciation of the elements, facets, approaches, rules, financial arrangements, actors, and power relationships within this setting is critical to achieving responsible groundwater use.

In particular, over the past two decades—with growing emphasis on sustainable approaches to managing resources—many societies have recognized the importance of bottom-up decision-making [5–8]. This has led to better alignment of actions and responsibilities among sometime-competing agencies and actors involved in governance [9,10], and to more efficient vertical integration among those entities [11].

Going beyond small-scale local institutional arrangements, observers have noted the importance of looking at the "big picture"—that is, linking groundwater governance to larger, macro-level, multisectoral policies [12,13]. Such a view permits linking groundwater governance to water governance more generally, and to the governance of intricately related sectors such as food, energy, environment, and trade—often characterized as the "nexus" [14–16].

At both small-scale and large-scale levels, the enhanced focus on the significance of institutions has permitted greater attention to issues of water security and its components of ethics, equity, access, and social justice. These notions, sometimes embodied in the term "hydrosolidarity"—an ethical concept intended to encompass sustainable aspects of water management that go beyond political and technical considerations—have begun to penetrate national and even transnational policies and practice [17] (e.g., the Water Integrity Network that aims to fight corruption in water governance worldwide; www.waterintegrity.org). While water politics continue to be driven by powerful interests at all levels (local to international), the growing prominence of bottom-up governance and its sibling attribute, transparency, has helped manage and transform water conflicts [18].

1.2. Availability and Access to Information and Science

Effective groundwater governance requires availability and access to information and science. Possessing information is very important for monitoring and assessment [3], and for negotiations over water allocation and management [19]. Accordingly, acquiring and analyzing data and information (both natural and social), and conducting research are foundational to good governance.

Among the needs are quantitative data—such as indicators—particularly for the development of early warning systems to increase disaster-preparedness [3]. In addition, collecting sociopolitical information is strongly recommended because of the significance of poverty, health, and vulnerability—all related to governance [14,19,20]. Furthermore, a key strategy in governance is to increase the co-production of knowledge, where the public actively participates in science—and this can be achieved via bridging organizations that act as intermediaries and can function at different scales [21–23].

However, the collection of sometimes sparse, dispersed, less-than-reliable data and information can be challenging and expensive, particularly for developing countries. Use of remotely-sensed data may be a cost-effective, reliable, and impartial way to skirt difficult on-the-ground searches [3]. Also, developing countries often have access to financial help from the international donor community to conduct research on groundwater resources. Multilateral and bilateral aid mechanisms can support data and information collection and management [24]. Moreover, collaboration and sharing among organizations can reduce research costs and overcome institutional asymmetries [25].

The benefits of better and more reliable data, more information, and more equitable access are self-evident, but there can be too much emphasis on this issue. At times, demands for those commodities may become action-averting strategies. So while calls for ever more authoritative information may be legitimate, they can also mask such weaknesses as lack of will, administrative and scientific inertia, bureaucratic bottlenecks, political meddling, insufficiency of trained personnel, or lack of resources.

1.3. Robustness of Civil Society

Engaging stakeholders in environmental decision-making was not always a prevalent mode of governance. However, over the past three to four decades, the procedure has gained acceptance across the world, especially in democratic societies. Involving a broad, representative, and active collection of stakeholders is essential to governance because that process is about influencing behavior [12]. To engage stakeholders effectively, it may be necessary to organize community and civil servants, who assist in public-participation processes where participants learn about relevant issues, actors, roles, and responsibilities, and become familiar with modes of complying with policies and regulations [3,14]. Strong leadership facilitates communication between stakeholders to ensure implementation [20].

However, enlisting and mobilizing stakeholders is not without its limitations. An important constraint that applies to all stakeholder processes is the difficulty of sustaining participant interest in a process that requires serious commitment over an extended period. Given the slowness of the decision-making process, even highly committed stakeholders become frustrated at the pace of responsiveness [26]. Stakeholder endurance palpably limits the empowerment of people to participate in policymaking.

Transparent, open, and fair mechanisms can help overcome this limitation [3]. The emerging social-media arsenal of Internet-based platforms and information technologies can help link and energize stakeholders [23]. Such connective tools facilitate the development of communities of practice that can exchange learning experiences from different regions [3]. With suitable technical and policymaking training of stakeholders, social-media tools hold potential to enhance substantially groundwater decision-making and environmental policymaking [3]. Nonetheless, even with the best tools possible, substantive stakeholder engagement may require redistribution of power and resources to sufficiently engage and empower disadvantaged and less organized stakeholders [3]. Further, even if civil society engagement is robust, implementation of particular policies or regulation may be uneven or may impact stakeholders in different, or perhaps inequitable ways.

1.4. Economic and Regulatory Frameworks

Regulations regarding groundwater use, quality, and monitoring determine how economic incentives and responses to those incentives influence groundwater-use practices and usability. Groundwater-users—like users of all goods and services—respond to price signals and other economic incentives. If water is available to the user cost-free, the potential for over-extraction or unsustainable groundwater use rises, especially where natural replenishment rates are slow.

Establishing water rights and measuring water use by individual users allow for providing behavior-changing economic incentives through pricing [11]. It is possible to recognize the necessity of water for living and still incorporate water scarcity into pricing through carefully crafted water-rate structures. However, even where water is metered and priced, water prices reflect the cost of extracting, treating, and delivering the water as incurred by the entity establishing these prices. There are often third-party impacts that should be incorporated into water rates. For example, water extraction by one user may cause higher energy consumption (from water pumps) and higher economic cost to a neighbor [3]. Establishing and sharing best practices for measuring third-party impacts can improve the policies governing groundwater management [3]. In addition, economic factors enter water-user decision-making via financing and paying for water infrastructure.

Water recharge and banking programs—where water is stored in the aquifer for future use—can optimize groundwater use based on intertemporal availability of surface-water supplies [27]. In addition, a carefully designed water-banking system may include mechanisms for marketing the right to pump water stored underground [27]. More generally, water marketing (whose frameworks might be varied) can permit market-based optimization of water allocation. Because water is necessary for basic living and since market control can lead to exploitation, there is a need for governmental oversight of water markets [13]. Therefore, analysis of the potential for water markets to improve groundwater allocation will necessarily need to consider equity and societal goals. While the expert community can offer insights on the scope of equity issues and societal impacts, it will be up to decision-makers to determine how to incorporate such considerations into groundwater governance approaches.

2. Materials and Methods—Case Study Approach and Analytical Structure

We review and compare observations from 10 studies that cover an expansive terrain—including the perspectives of geography, thematic content, problematics, and instructiveness. We selected these studies based on their location, quality, authoritativeness, and most of all, their direct, targeted attention to groundwater governance. We also chose them to represent diverse regions of the world—including developed and developing nations—and because they are rich in data, observations, conclusions, and recommendations.

We rely on experiences, observations, and findings steeped in real-world explorations of groundwater governance. Through records of earlier published cases, we overlay our own composite observations, which highlight context while seeking to identify commonalities and generalizable lessons.

The first five studies (published between 2000 and 2011) were important references in Thematic Paper Number 5 by Varady et al. (2013) [3] and helped provide a basis for that report's findings. To reflect more current understandings—from a limited pool of post-2011 groundwater case-study publications with an emphasis on governance—we selected five studies that are of comparable breadth and quality to the other five (See Figure 1 and Table 1). We elected to limit our sample to 10 studies to permit in-depth review and analysis of the cases, while identifying broad trends and patterns in groundwater-governance case research.

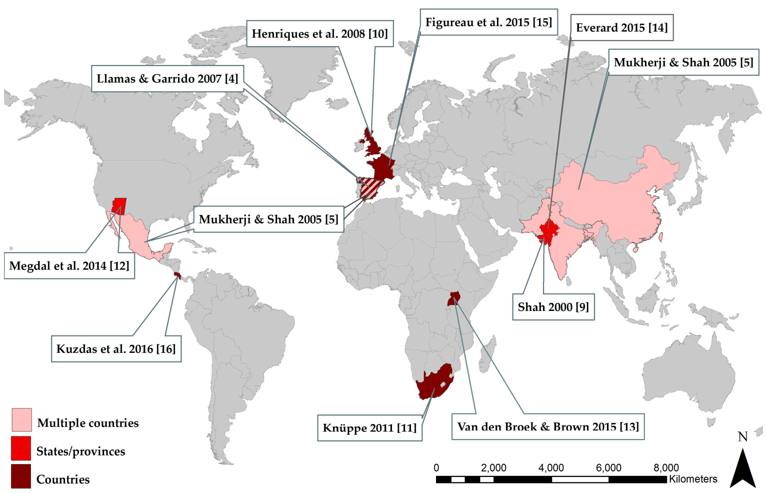

Figure 1. Location of case studies. This map illustrates the diversity of the geographic location of the case studies analyzed in this paper.

Table 1. Selected case studies. The 10 case studies reviewed, given in order of year of publication.

Study	Location	Summary
Shah (2000) [28] [a]	Gujarat, India	Looks at a social movement in western India, where a groundwater-recharge initiative grew to a large social phenomenon.
Mukherji & Shah (2005) [14] [a]	India, Pakistan, Bangladesh, China, Spain, Mexico	Examines benefits & disadvantages of groundwater use, and recommends a change in paradigm: from management to governance.
Llamas & Garrido (2007) [29] [a]	Spain	Explores the "silent revolution" phenomenon, where developers use ground-water with little or no scientific, technological, or administrative control; examines stakeholder participation in groundwater management.
Henriques, Holman, Audsley & Pearn (2008) [30] [a]	East Anglia and North West England	Uses interactive Regional Impact Simulator tool to examine impacts of farm-level cropping decisions in regional water availability, including multi-scalar approach at field, farm, sub-catchment and catchment, and regional levels.
Knüppe (2011) [20] [a]	South Africa	Describes qualitative assessment of groundwater management that includes expert interviews from entities including national government, research and conservation organizations, and consultants.
Megdal, Dillon & Seasholes (2014) [27] [b]	Arizona, USA	Explores policy perspectives of managed aquifer recharge, or "water banking", in Arizona, USA, and the context in which this strategy is implemented.
Van den Broek & Brown (2015) [31] [b]	Uganda	Analyzes impacts of two decades of managing rural groundwater in Uganda, following the Community Based Management (CBM) paradigm.
Everard (2015) [32] [b]	Rajasthan, India	Studies the successful community-based groundwater-recharge program in a region of groundwater-level decline and related socioecological degradation.
Figureau, Montginoul & Rinaudo (2015) [33] [b]	France	Offers empirical assessment of opposing groundwater-management regulations strategies that may be implemented in five groundwater basins in France, identifying barriers and factors that can facilitate implementation.
Kuzdas, Warner, Weik & Vignola (2016) [34] [b]	Guanacaste, Costa Rica	Provides a transdisciplinary, multi-criteria sustainability assessment of groundwater resources, based on current management approach in five governance regimes in Guanacaste, Costa Rica.

Notes: [a] Papers from Thematic Paper No. 5 (Varady et al., 2013) [3]; [b] Papers from recent literature.

We approached our analysis by selecting four practical elements (or action steps) of governance employed in the thematic paper [3]. These elements—institutional setting, availability and access to information and science, robustness of civil society, and economic and regulatory frameworks—are instrumental to groundwater governance and policy. We also worked inductively to query systematically the updated case studies using these four governance elements and to identify commonalities in the cases.

Our aim is to report on the broader trends and patterns across the cases and to illustrate the most pertinent or interesting findings within the various cases. As such, we do not treat every case equally. While we acknowledge that other combinations of articles plausibly could entail such a review, our selection emphasizes diversity in location, quality, relevance, and authoritativeness, and in so doing, best addresses the four identified governance elements. This approach enables us to take the next step to see what animates governance at ground level in diverse settings.

3. Results—What Do the Case Studies Reveal?

3.1. Institutional Setting

As noted, effective groundwater governance relies on a strong institutional setting. Legitimate, durable, flexible, responsive, and above all, viably funded institutions are indispensable elements of a nation's or a region's ability to manage its groundwater resources. However, those attributes—important as they are—can be read as platitudes. In real-world settings, what are some the ingredients of a strong institutional base? Our 10 case studies offer useful insights into this question.

Virtually all the studies consider groundwater policymaking as strongly dependent on institutional factors. Unsurprisingly, the role of the state and its various agencies is a hub for achieving good governance. In this vein, many of our authors acknowledge the importance of state agencies and ask whether and how they might be more effective.

3.1.1. Role of Government

Governments sometimes have responsibilities that exceed their human and financial capacity. Governing groundwater is a highly complex and fraught activity; it depends upon both the physical configuration of groundwater structures (e.g., wells, pumps, etc.) and an area's reliance on groundwater resources. These considerations include the following variables: (i) per-annum volume of groundwater abstractions; (ii) number and type of groundwater structures; (iii) percentage of population whose livelihood depend on groundwater; and (iv) the prevailing political system [14]. To navigate such complications, rules and procedures are indispensable.

In order for governing institutions to have power over groundwater resources, they should be able to make policy. In Arizona, USA, the state water agency—the Arizona Department of Water Resources (ADWR)—is enabled to make policy. The regulatory water-rights framework of the region's major surface-water source, the Colorado River, provides ADWR with the legal right to store water via managed aquifer recharge [27]. The agency also has authority to limit urban growth through an Assured Water Supply program, which mandates that residential developments have a guaranteed 100-year water supply [27]. Yet even where favorable institutional conditions exist, they can be constrained budgetarily, politically, and managerially.

Elsewhere, writing broadly about countries in three continents, Mukherji and Shah (2005) [14] found that if agencies are to function effectively via rules and procedures, while devising policies and making laws may be feasible, enforcing them usually proves to be far more difficult. Knüppe (2011) [20], considering South Africa, confirms that legislation alone is insufficient to address groundwater-management problems; it is equally necessary to educate and raise awareness, induce cooperation among existing networks, and increase stakeholder engagement. But when state agencies are absent altogether or weak, Van den Broek and Brown (2015) [31] found in Uganda that this sort of lacuna (as promoted by Community Bases Management (CBM)) leads to unsuccessful groundwater-governance outcomes. However, there may be times when government's role can remain negligible, yet without harm. A case study in India [28] shows that communities by themselves may be able to improve the health of a watershed with complete autonomy—particularly when, with strong community leadership, positive externalities are rapidly internalized; in this case, the effort was tied to religious beliefs.

Van den Broek and Brown (2015) [31] suggest a middle ground: *the role of government should change, but not disappear*. Reluctance to change can be manifested in a country's legal framework, where in extreme cases, conservation actions can actually be illegal, underlining why change is essential and should be encouraged. In Rajasthan, India, Everard (2015) [32] illustrates reluctance to change; there, locally built water-harvesting structures are considered illegal, if nevertheless unenforced. Van den Broek and Brown's (2015) [31] work in Uganda shows that the state should not abandon groundwater-resources governance. The authors recognize that assigning to a community the full responsibility to manage groundwater resources is generally unsuccessful.

3.1.2. Matching Administrative and Hydrologic Units

In the past, water management—as with all forms of government-led management—was achieved within formal administrative units (nations, provinces, states, districts, municipalities, and other divisions). While this approach may have been efficient bureaucratically, it failed to account for landscape, natural processes, communications, and societal practices. In short, it disregarded hydrologic and cultural boundaries. Everard's (2015) [32] study in Rajasthan, while recognizing barriers to radical organizational transformation, exemplifies the need for administrative units to match as closely as possible hydrological ones. The techniques used to build local water-harvesting structures used traditional knowledge and social institutions. The Non-Governmental Organization (NGO) leading this effort, Tarun Bharat Sangh (TBS), responded to demands to maintain traditional village management institutions. One example of such an institution is the Gram Sabha, the water-management decision-making body. TBS created "water parliaments" that group villages within a catchment area to create unified policies [32].

In the United Kingdom, as well, matching functional units is important. Henriques et al. (2008) [30] point out that water is transferred over long distances, and that abstractions are not necessarily linked to points of use. For this reason, the authors model water supply and demand at the regional scale. However, sometimes there can be a mismatch between regional boundaries and catchment boundaries. In this case, the authors scaled catchment water availability in their hydrological model according to proportion of catchment area outside the regional boundary.

The Arizona study also addresses this issue by describing the flexibility of the recharge program that allows a recharge project to have a different location than the point where the groundwater withdrawal occurs. This locational disconnection has eased the use of this renewable resource, but increased the risk of localized overdraft. Still, Arizona has attempted to match hydrologic and administrative units. The regulatory regime established in the state's Groundwater Management Act (GMA) is aligned with Active Management Areas (AMAs), the units created for the state's most populated groundwater basins [27].

Management via traditional administrative units further complicates planning and coordination. Henriques et al. (2008) [30] observed that urban- and regional-planning policies affect landscape and hydrology, including evapotranspiration and surface sealing. More generally, Kuzdas et al. (2016) [34] found that in Guanacaste, Costa Rica, a lack of clear regional-planning objectives and poor coordination between national- and local-level decisions lead to mismatches in outcomes and local community needs and sustainability.

3.1.3. Financing Practices

Financial support for water agencies is always of the utmost importance, particularly in developing countries. In Costa Rica, Kuzdas et al. (2016) [34] reported that shortfalls can lead to corruption, sometimes manifested as the approval of development projects as *quid-pro-quos* for accepting developers' donations. Sometimes corruption practices can be subtler yet still damaging, when governments "do nothing" to stop the overexploitation of the aquifers [34]. One way to lessen such questionable practices is to assure that water professionals receive equitable salaries [34].

In India, corruption cases are also evident and often with seriously adverse results. Everard (2015) [32] observed that the Indian government granted fishing permits to contractors, a practice that allowed them to exploit restored ecosystems. This became a huge social conflict with local communities that were personally involved in restoration efforts. Those communities did not allow the contractor to access the river; and the angry contractor, in revenge, poured pesticides into the river killing fisheries, negatively affecting local populations [32].

In Uganda the situation is somewhat similar. Van den Broek and Brown (2015) [31] noted that lack of salaries for people collecting fees led to corrupt practices, because the collectors spent the fees for personal expenses, attributing their behavior to their lack of salaries. In addition to corruption, lack of funding can result in disengagement and lack of continuity. Trained Water Use Committee members in Uganda were unwilling to work without pay [31]. These individuals lacked capacity-building opportunities, forgot their original training, or simply decided to leave the community [31].

However, corruption cases are not exclusive to developing countries. In Spain, e.g., Llamas and Garrido (2007) [29] found that subsidies can become "perverse" by encouraging corrupt practices.

For example, European Union subsidies intended to decrease groundwater abstractions for 10 years failed to stop illegal pumping and drilling of new wells [29]. The intent of regulating groundwater is to reduce corruption but this practice, too, requires funding. Mukherji and Shah (2005) [14] recommend regulation through registration of wells and licensing, and pricing policies, particularly in developing countries. However, installing groundwater-monitoring networks represents a high cost and presents a serious obstacle for regulators.

Conflict resolution also requires financial investment. In France, inadequacies within agencies prompted a need for non-agency intermediaries, via "joint liability contracts," to solve social conflicts [33]. And similarly, in Costa Rica agencies brought in a social scientist to facilitate deliberation in a workshop that aimed to evaluate five governance approaches (scenarios) for groundwater governance [34].Without doubt, funding constitutes an overarching issue that affects many aspects of groundwater governance. The following sections include reference to issues and challenges that emerge when there is lack of enough funding.

3.1.4. Government as Supplier or as Custodian?

Whether agencies are amply or inadequately funded, and whether they are centrally controlled or locally managed, many observers have noted a shift in their role: *from "supplier" to "custodian"*. The Rajasthan study points to potential conflict when government does not act as a resource custodian, and instead grants rights such as fishing permits to contractors to exploit restored ecosystems. As explained above, conflict with local communities resulted in negative impacts for everyone—the contractor did not get access to the river, and the communities suffered adverse effects from the poisoning of the fish [32].

By contrast, some studies illustrate instances when a government's resource custodianship can be strong. For example, in England and Wales, according to Henriques et al. (2008) [30], the Environment Agency enforces control of abstractions through a system of licenses and drought management by water utilities. In South Africa, the government's custodianship is evidenced in the 1998 National Water Act, the country's principal water-resources-management legal instrument. In this law, the ecosystem's needs are included in the principle of "Ecological Reserve", according to which, environmental requirements must be "reserved" before any allocation for human use. However, even with ecological needs legally accounted for, sustainable groundwater governance remains challenging in South Africa [20]. In the case of Arizona, the state government became the resource custodian in 1980 when it passed the GMA after a period of overdraft that reached a critical point in the late 1970s. Megdal et al. (2014) [27] describe the GMA's function in requiring new urban developments to use renewable water supplies instead of groundwater.

In Costa Rica, the need for resource custodianship is evidenced by overexploitation of aquifers (a partial consequence of greedy practices), excessive reliance on supply-side approaches such as augmentation, a lack of flexible water management frameworks, and insufficient government oversight [34]. Yet, such government oversight is sometimes unwelcome, as shown in the periodic instances of resistance and discontent by French farmers when there was a shift from open access resource to a regulated one [33].

3.2. Availability and Access to Information and Science

Our case studies review showed that availability and access to information and science is critical to groundwater governance, pointing to a need to stimulate research on groundwater resources. However, a lack of funding, particularly in developing nations, limits availability and access to reliable information.

3.2.1. Research Needs and Transparency

The studies show that effective groundwater governance should be based on research on the resource itself and on interrelated sectors including agriculture, tourism, mining, forestry, and the environment—all at multiple scales. Effective research requires expertise on groundwater and its connected sectors. However, in some countries such expertise is often in short supply. In South Africa, for instance, Knüppe (2011) [20] describes some bureaucratic issues where a paucity of trained personnel and facilities limits research and progress on effective approaches to governance.

In Arizona, where research capacity is ample (both in terms of field investigations and university-like research), applied science on groundwater resources is fundamental for groundwater governance. There, water from the Colorado River is transported via canal by the Central Arizona Project (CAP) to recharge aquifers for storage (i.e., managed aquifer recharge, or "water banking"). However, in order to "evaluate hydrologic feasibility", an Arizona study on banking used quantitative data derived from groundwater-flow models. That evaluation process also considered water quality and potential damage to adjacent properties [27].

The U.K. experience reveals that groundwater-resources research also should consider a multi-scale approach (e.g., field, farm, sub-catchment and catchment, region) [30]. In addition, sustainable management requires not only access to information, but also sustained data collection for monitoring quality and quantity [20]. In Spain, Llamas and Garrido (2007) [29] similarly found that more and better hydrological data are needed to reduce uncertainty in groundwater management and to make better decisions in general.

Our review also revealed that research should include the effects of urban-planning policy. As large water-users, municipalities are becoming critical actors for groundwater governance in terms of land-use change that affects hydrologic processes. The UK study confirms that urban- and regional-planning policies affect landscape and hydrological effects, including evapotranspiration and surface sealing [30]. And lack of clear planning objectives can lead to a mismatch in outcomes that negatively affects community needs and sustainability [34].

However, research can be biased and manipulated. In Uganda, van der Broek and Brown (2015) [31] found that the government over-reported official figures of functioning pumps in order to meet sustainable development goals. In Costa Rica, Kuzdas et al. (2016) [34] observed that when the government does research without the participation of local communities, there is a risk of bias in studies that explore the feasibility of development projects. Transparency in data availability—as well as broader development planning—is necessary to avoid conflicts and suspicions [33,34]. Yet transparency, while desirable in theory, may trigger further conflict. In the case of France, although institutional stakeholders believed that transparency would enhance responsible behavior, most farmers did not believe that making data available would result in higher compliance of rules [33].

3.2.2. Funding for Research

The case studies suggest that the degree of financial resources required for research frequently impedes sustainable groundwater governance, particularly in disadvantaged, developing societies. There, the challenges to obtaining access to high-quality data are substantially greater than in developed nations [14,34]. NGOs have filled this gap to some degree. The Rajasthan study demonstrated that such organizations might sometimes function as mediators while also attracting funds from the international community [32]. Developed nations are not exempt from funding challenges. The South African case reveals that insufficient funding for groundwater-resources research and for training water-management personnel negatively affects pricing systems and legal provisions [20].

3.2.3. Information for Negotiation

Our review found that water allocation and management require reliable information and that the use of indicators promotes transparency. In Costa Rica, Kuzdas et al. (2016) [34] learned that judicious use of such indicators helped identify key water-governance challenges, and that transparency engaged stakeholders in the decision-making process.

Lack of reliability reported in the Uganda case study shows that official over-reporting of water-pump functionality is either a case of corruption or lack of capacity causing a serious impediment to development [31]. A study by the Uganda Ministry of Water and Environment reported that 64 percent of the rural population had access to water (through hand pumps) and that 85 percent of the pumps functioned properly. However, a study by Koestler et al. (2010; cited in van den Broek and Brown 2015 [31]) determined that in actuality only 40 percent of the pumps were functional. This finding suggests that government-funded projects may overestimate such indicators as pump functionality for self-serving purposes. In this instance, the government would like to report that they are in compliance with Uganda's constitution and national policy, which stipulates that that by the year 2015, 77 percent of the rural population would have access to water and 90 percent of the pumps would be functioning [31].

Access to information and scientific research is critical to governance because these commodities can be used to enhance political leverage. The Arizona case exemplifies how these capabilities can help in negotiations with neighboring governments. Because CAP water was "underutilized" (that is, used at less than permitted, allocated amounts) and because there was a risk of losing this water to a large and powerful neighboring state, Arizona decided to use CAP river water to recharge some of its aquifers. The different recharge projects range in scale, but infiltration rates are carefully monitored. Thanks to this information, Arizona has been able to take—and save—its entire allocation of Colorado River water. This full utilization, along with interstate managed aquifer recharge (discussed above), were important to interstate negotiations on sharing of Colorado River shortages [27].

3.2.4. Socioeconomic Data Needs

The case studies uniformly suggest that socioeconomic factors are critical for groundwater governance and that wherever possible, research should factor such considerations. In Spain, Llamas and Garrido (2007) [29] found that social factors are the primary cause of environmental problems, more so than natural factors. This was also true for South Africa, where Knüppe (2011) [20] describes that achieving sustainable groundwater-resources management requires integration of the socioeconomic and hydrogeological dimensions. For example, aquifer properties and their relationship to human wellbeing are of equal importance because of the linkages between aquifer properties and poverty, vulnerability, and health [20]. Similarly, in Costa Rica, Kuzdas et al. (2015) [34] concluded that water issues are linked to socioeconomic issues faced by communities that are proximate to ecotourism development sites. These communities incurred such negatives consequences as loss of land, low wages, and increased prices. In addition to tourism, other economic sectors that depend on groundwater resources include agriculture, and mining (20), therefore researching how much groundwater contributes to these economic activities is crucial. In the UK, Henriques et al. (2008) [30] state that water demand is linked to population, which is the dominant socioeconomic indicator. In India, Mukherji and Shah (2005) [14] concur, arguing that although hydrogeological data are greatly needed, having reliable socioeconomic data is as important. For example, in India, livelihoods are directly linked to water levels. Everard (2015) [32] found that water levels directly affected women because when levels were restored, women became able to engage in productive activities rather than spend entire days foraging water. Mukherji and Shah (2005) [14] include the percentage of population whose livelihoods depend on groundwater along with its political systems as one out of three factors that may explain the success of groundwater-demand management in some countries and not in others. More research is needed on the economic and social dimensions of groundwater use and on the institutions that govern this use [14].

3.3. Robustness of Civil Society

Our case studies concur that groundwater governance is a community process that requires participation by governmental and nongovernmental groups. However, participatory governance is often lacking, especially in places where the status quo favors certain groups that use the resource, or when it promotes inequities in access to groundwater or in the implementation and exercise of regulation. We also found that many stakeholders indicate that they would like to be involved in knowledge production. As a major reason, they cite the desire to reduce the potential bias of research organizations—particularly when these are sponsored by local government, which is frequently distrusted. The studies also revealed that educating groundwater-user communities and promoting learning in participation is a key to groundwater governance, as is wide communication of successful and unsuccessful strategies. Finally, the studies frequently highlighted that leadership is a key element in stakeholder engagement.

3.3.1. Participatory Governance

Our review reveals that groundwater governance is undertaken by diverse governmental and nongovernmental stakeholders, including policymakers, public-sector organizations, and private-sector organizations [20]. In Arizona, the CAP, which delivers water to the largest cities in the state (Phoenix and Tucson) and to sovereign Native Nations, is governed by a 15-member board of directors that represents each of the counties served by CAP [27]. In India, a local NGO created the "Rashitriya Jal Biradari" (national water brotherhood), which facilitated a community-led groundwater recharge effort in a semiarid region of Rajasthan, India [32]. The group includes water experts, farmers, NGOs, researchers, voluntary organizations, social groups, and social scientists who meet once a year to discuss management issues. The Llamas and Garrido (2007) [29] study of groundwater governance in Spain indicates that the timing of engagement is crucial. A community-based governance approach that engages stakeholders at the outset is a key factor for successful management of aquifers.

In some contexts, participation is notably lacking. An assessment of alternative governance regimes for Guanacaste Province, Costa Rica, highlighted a call by stakeholders for more participatory processes [34]. Mukherji and Shah (2005) [14] found reluctance in Mexican farmers to join governance institutions because the main institutional goal usually is to limit groundwater abstractions, which is something farmers are not willing to do.

3.3.2. Top Down or Bottom Up?

The case studies surveyed indicate general agreement that groundwater governance should be decentralized and must involve local communities. According to Knüppe (2011) [20], governments can support bottom-up approaches to water governance by funding technical services, infrastructure, capacity building, and coordinating initiatives. In Spain, Llamas & Garrido (2007) [29] also suggest such a balanced approach. They conclude that it would likely be beneficial to collectively and inclusively manage aquifers, with some control from water authorities.

In a recent study in France, Figureau et al. (2015) [33] explored the role of Groundwater Users Associations, which attempt to adapt rules to local contexts and facilitate social acceptability. The most desirable management mode among three evaluated approaches was the strategy that empowered local farmers while reducing government interference and promoting self-regulation.

The case studies showed that bottom-up, more community-based approaches require vertical integration. In Arizona, there is a kind of coherence across scales that integrates local actions with state policies. The state legislature passed the GMA creating an institution to administer it, ADWR. This institution has an administrative framework that regulates water rights [27]. In his study of groundwater in Rajasthan, Everard (2015) [32] demonstrates the advantages of vertical integration. He points out that (i) state and central governments have significantly different water-management perspectives than local communities; and (ii) that the government has more institutional and legal power than village councils, NGOs, and water parliaments. This unequal balance leads to suboptimal groundwater decision-making (and other resource governance). Comparably, in Uganda, Van den Broek and Brown (2015) [31] observed that Water User Committees, working without support from the national government, lack legal status and authority and were generally unsuccessful.

Everard's (2015) [32] study—which explores late colonial and early post-independence centralization of water governance in the state of Rajasthan—illustrates the need to decentralize groundwater governance and involve local communities. Everard found that centralized approaches resulted in a loss of local indigenous knowledge about water harvesting structures and a corresponding shift in the value of water, disengaging the local community in the maintenance of water structures. This abandonment of local water management led to unsustainable livelihoods, degraded ecosystems, and societal collapse. However, during the mid-1980s, an NGO—TBS—worked with local communities to restore water systems in what they called "community self-reliance through resource conservation". This permitted construction of traditional water-harvesting structures with successful results for both social and ecological systems [32].

Similarly, in Costa Rica, Kuzdas et al. (2016) [34] determined that top-down approaches to groundwater governance would not meet sustainability goals. In Uganda, van den Broek and Brown (2015) [31] noted the desirability of involving the community in groundwater governance, but their case study concludes that leaving the process entirely to the community does not work. In addition, the appropriate Water User Committee (WUC) lacked legal standing, resulting in its inability to secure operation and maintenance funds for water pumps. The authors also found that community meetings that bring up the need to pay fees discouraged participation—and those members of the WUC charged with collecting such fees are often seen as enemies.

In countries with highly centralized governments, such as China, governments are expected to enforce groundwater-use rules. However, there, implementation of regulations is not very transparent and has not been studied [14]. In South Africa, centralization of power has challenged the achievement of sustainable groundwater management [20]. Equity, effectiveness, and efficiency in groundwater management are best accomplished through a decentralized management system, according to the papers reviewed here.

3.3.3. Co-Production of Knowledge

As a body, the case studies evince a desire by stakeholders to be engaged in the production of knowledge for groundwater governance. Stakeholders in Guanacaste province in Costa Rica, for instance, believe that there is a need for research on the aquifer's capacity and recharge potential in order to improve governance. Although complex quantitative hydrogeological models may not be suitable for the coproduction of knowledge, other types of assessments can be feasible. For example, in western India, where a social movement harvested rainwater to recharge wells, a series of NGO-led technological experiments in water-conservation strategies (in-situ recharge and water-use reduction) used traditional water-harvesting methods. The group experimented until it obtained a simple, inexpensive way to direct rainwater to a tank that removes silt and allows clean water to recharge wells [28]. In Guanacaste province in Costa Rica, stakeholders believe that there is a need for research on the aquifer's capacity and recharge potential in order to improve governance. However, to minimize risk of bias and to ensure accuracy and legitimacy, government-led studies that explore the feasibility of development projects should include input from and contributions by local communities [34].

3.3.4. Awareness: Education and Communication

The cases underlined the importance of education in stakeholder engagement. Stakeholder participation in groundwater governance is essential for sustainability in the use of the resource, and to succeed, the process should include informed and educated groundwater-users [29]. Educating the public and raising awareness of the importance of groundwater resources is a fundamental principle of effective groundwater governance [20]. Education and awareness programs are likely to result in greater willingness for community participation when some stakeholders may be reluctant to engage [14].

The selected studies suggest that communication is a central determinant of successful groundwater governance. Shah (2000) [28] reported that audio and video recordings enhanced public participation in a western Indian social movement to recharge wells in India, particularly when the leader is the speaker in the recordings or in person. Another effective way to communicate successful experiences is through money. Shah (2000) [28] reports that demonstrating the attractive cost-benefit ratio of well-recharge expenses versus the economic benefits of a recovered watershed and increased groundwater levels served as anecdotal experience to convince other communities. In addition, the distribution of illustrative pictures of working well-recharge technologies helped the proliferation of India's water conservation movement [28].

3.3.5. Role of Leadership

The robustness of civil society remains highly dependent on the availability and quality of leadership, which determines the degree of stakeholder engagement. Our two case studies in India highlight this. In Gujarat, traditional Hindu spirituality and ethics played a role in a social movement to conserve water and recharge wells. There, charismatic and skillful leaders interpreted and narrated scriptures (*Katha-kar*), thereby demonstrating great power to direct community residents [28]. In the other Indian case study, an NGO leader, Rajendra Singh, advocated traditional knowledge and brought necessary funding to initiate water-conservation techniques. He embodied the role of the strong leader needed to manage groundwater effectively [32]. In South Africa, Knüppe (2011) [20] observed that strong leadership that improves guidance and communication is a vital element of governance. A leader, she noted, must be educated, open, flexible, and trustworthy.

3.4. Economic and Regulatory Frameworks

The diverse set of case studies provides evidence that water-users generally respond to economic incentives, be they charges or subsidies, although outcomes may not fully align with expectations. The studies also illustrate some of the complications associated with changes in economic policies, especially for the agricultural sector and in locations where water previously had not been priced. They also demonstrate that the efficacy of market-like mechanisms in achieving policy objectives depends on underlying water rights and other elements of the regulatory framework, along with regulatory oversight. This underscores the importance of economic policies related to electricity.

3.4.1. Economic Instruments

Figureau et al. (2015) [33] look at economic instruments to promote sustainable groundwater use in France; these can be positive (e.g., subsidies, payments) or negative (e.g., pricing, taxes, penalties). There, pro-social policies have been employed to promote fairness, accountability, trust, moral inclusion, and reputation—and a combination of both economic incentives and pro-social policies. Not surprisingly, the study found that farmers prefer pro-social policies over economic instruments, most likely because these are policies with which farmers are familiar. The authors found that when evaluating the effectiveness of a strategy based on economic instruments (payments and penalties), participants recommend aligning the economic instrument to local conditions (economic, hydrological, and climatic). They discussed the level of the economic instrument (penalty) that should avoid farm bankruptcy and be based on tradeoffs between long-term viability goals and efficiency. Their finding that most farmers would prefer to pay the penalty rather than change their practices suggests that penalty rates were not set to provide behavior-changing economic incentives. The study found that penalties to induce water conservation might have had the opposite effect. They found that farmers who pay the imposed penalty might feel that they have the right to exceed their water allocation. This points to the need for effective compliance mechanisms. Comparably, in Uganda, Van den Broek and Brown (2015) [31] identified the inability of WUC to collect water fees from users as a reason for the failure of CBM to manage groundwater. The feasibility of implementing economic policies and monitoring compliance needs to be considered.

3.4.2. Communal Ownership

Contributions toward infrastructure influence behavior. The case study in Rajasthan found that behavior is tied to economic cost. There, the NGO TBS requires that 30 percent of the cost of structures be provided by the community in order to ensure "communal ownership and continued maintenance" [32]. However, community contribution toward the cost of water pumps does not necessarily foster a sense of ownership [32]. The Ugandan case study failed to find that an upfront payment for pumps resulted in intention to maintain the installed pumps [31]. The study discovered that the reason for resistance to pay for operation and maintenance of pumps in Uganda was a general belief that water should be free of charge. People expect the government or NGOs to pay for infrastructure, and changing to a system that requires payment for previously free water services can be difficult [31].

3.4.3. Subsidies

Conceptually, subsidies to support desired behaviors can have the same economic impacts as economic charges to discourage groundwater over extraction. Yet, Llamas and Garrido (2007) [29] found that subsidies also can have perverse effects, as discussed in Section 3.1.3 above. They reported that European Union (EU) subsidies given to Spain to compensate the decrease in groundwater abstractions for 10 years did not stop the drilling and use of illegal wells. Another case study in Spain concluded that EU subsidies resulted in a temporary halt to groundwater abstractions, but not in positive collective action [14]. This study did find that income-compensation schemes have been effective in decreasing groundwater abstractions. The confidence that water-users have in delivery of promised economic support will influence future effectiveness of economic policies. Shah (2000) [28] found that when the government of India promised subsidies to the people who participated in the well-recharge movement, some people delayed their participation to wait for the subsidies, which never materialized.

In their case study of Mexico, Mukherji and Shah (2005) [14] found that substantial electricity subsidies have served well as a "carrot" to well-owners to register their wells. However, monitoring water volumes of abstraction remains challenging. They report on several strategies employed by agencies—with differing levels of success—to manage groundwater demand, including: regulations and enforcement, modification of property rights and new institutions such as water markets, and economic incentives. Likewise, Knüppe (2011) [20] found that economic instruments available to manage groundwater demand include a range of policies, such as subsidies to water-saving measures, subsidies to efficient irrigation technology, and subsidies for water-treatment technologies offered to industries and municipalities.

3.4.4. Changes in Crop Types

How agricultural water users respond to economic incentives can vary widely. Farm subsidies designed to influence the mix of crops produced has the potential to affect water use [30]. Henriques et al. (2008) [30] asserts that economic instruments to affect agricultural water demand should not only include water pricing, but also consider markets and food production priorities. Moreover, the study identifies the important role of the cost of inputs, such as fertilizers and labor, in agricultural production and associated water use. The authors recommend that regulatory restrictions on water use for irrigation, such as licensing, or economic instruments, such as volumetric abstraction costs, must be used with caution and should include the associated environmental costs. However, for developed countries, Mukherji and Shah (2005) [14] recommend regulation through registration of wells and licensing, and pricing policies.

In considering future scenarios, Henriques et al. (2008) [14] found that controlling water demand in agriculture through water pricing may result in the substitution of high-value crops for lower-value crops. While such behavior may be seen as a rational economic response by the irrigator to higher water rates, it could in fact result in higher volumes of water used.

3.4.5. Water Pricing

Water pricing may affect decisions to use surface water rather than groundwater. In the U.S. state of Arizona, the statutory recharge and recovery framework allows for farmers to partner with municipalities or with the Arizona Water Banking Authority so that irrigators use less groundwater and more surface water. The nonagricultural partner buys down or subsidizes the cost of surface water so that the irrigators will use surface water instead of lower-cost groundwater, to which the irrigators have extraction rights. The partner, such as the Banking Authority, accrues credits for future recovery, with a small "cut to the aquifer" not eligible for future recovery. The credits are granted by the state water agency through a carefully enforced permitting and accounting system. This regulatory framework has been effective in meeting statewide goals to store surface water in times of availability for future use during shortage [27].

3.4.6. Water-Energy-Food Nexus

Electricity is the most crucial operating cost for groundwater pumpers. In India, in particular, the instrument that is most commonly used to control groundwater extractions is electric supply. Shah (2000) [28] identifies a ban on electric supply as an effective means to reduce extractions. He reports that the electricity supplier—the state of Gujarat—is a monopoly that can play a significant role in "disciplining private pumpers by skillful use of electricity pricing and supply policies as levels for groundwater demand management" (p. 200).

Mukherji and Shah (2005) [14] clearly see the connections of food and energy policies. They identify a window of opportunity to manage India's groundwater economy through the rationalization of electricity supply. They also identify other control instruments—e.g., electricity subsidies, and policies for foodgrain production. Elsewhere, Henriques et al. (2008) [30] note that in the UK climate change mitigation policies could alter crop production strategies to favor non-food bioenergy crops that are linked to water use. However, while identifying such potential levers, Mukherji and Shah (2005) [14] suggest caution and discretion, acknowledging that practical, political reasons may pose a barrier to electric bans and subsidy reductions and changes in crop-subsidy policies. They also note that not all measures of water governance work everywhere, and that contextual differences play a major role in the success of groundwater governance.

3.4.7. Role of Markets

Market mechanisms are playing an increasing role in water allocation. Henriques et al. (2008) [30] describe water markets as an economic instrument that can replace drought regulations in the UK. However, the authors warn that this mechanism leads to changes in water use (e.g., away from agriculture and more towards municipal use and even leisure activities such as golf). Therefore, this economic mechanism does not necessarily decrease water demand. When Figureau et al. (2015) [33] studied scenarios of water-management strategies among stakeholders in France, they found that farmers believe that water markets would undermine the "collaborative spirit" that a pro-social strategy promotes. And Shah (2000) [28] attributes the worst groundwater catastrophe in the Gujarat region in India to water markets that promoted agricultural expansion and economic growth beyond the aquifer's carrying capacity. The study further identified a need to regulate water markets in order to restore environmental health.

In Arizona, the integrity of the managed aquifer recharge process is maintained by accountability including permits, monitoring, and reporting [27]. In addition, the flexibility of the water-banking process in Arizona—also known as "mass-balance approach," where recharge is done in one place and abstractions in another—is supported by extensive monitoring. Arizona's water banking strategy has been extended to the neighboring state of Nevada. This complex mechanism to store Colorado River water in aquifers for future use by another state requires an accounting system that tracks quantified rights, and permits and fees associated with storage and future retrieval [27].

In Spain, groundwater markets are difficult to assess. Llamas and Garrido (2007) [29] describe that the 1985 Water Act declared groundwater as a public domain; before 1985, groundwater was considered a private domain. Groundwater use prior to 1986 could continue to function as private property using the same amount as before, but new abstractions require a permit [29]. However, the government has not been able to get the private wells built before 1986 registered and the volumes extracted are still unknown [29]. Water markets were introduced in the late 1990s without much impact on water reallocation; but groundwater markets are not supposed to be pertinent because groundwater was somehow still considered a private asset, therefore it could be leased, bought, or sold like any other asset. There are informal/illegal groundwater markets in Spain, but data on these are not trusted [29]. So, groundwater rights in this country are unclearly established mainly because most of the wells are illegal, with the exception of the Canary Islands, which have a different water code because groundwater is the main water source [29]. So, basically all groundwater in this region is privately owned [29].

Mukherji and Shah (2005) [14] indicate that water markets work better in areas where water is not scarce. In water-short regions, water markets could actually result in resource depletion. Long-term water-storage credits under the Arizona system are in fact marketable. While there has been increased activity in the marketing of long-term water storage credits in water-scarce Arizona, analysis of the economic and water use implications of sales of storage credits awaits further analysis [27,35].

4. Discussion—Lessons Learned: Context and Commonality

In this section, we digest the rich materials consulted in 10 case studies in order to draw some lessons (Table 2). The papers range across five continents and treat developed and developing societies. It could not be clearer that—at all levels—contextual considerations are (and ought to continue to be) the primary determinant of governance policies based on traditions and practices. This reflects a growing recognition in water governance of the importance of mixed-governance strategies that appeal to multiple values and fit into local circumstances [36]. Context in water governance is recognized to shape collaboration, innovation, and on-the-ground implementation of projects and policies [37]. Yet many of the observations in our case studies converge. While we emphasize that there exists no single, all-purpose toolkit for sustainable groundwater management, we believe that the take-home messages from the ensemble of our sources do provide valuable tips for planners, decision-makers, managers, and stakeholders.

To discuss these messages, we follow the organization of the previous sections of the paper. Thus, we consider, in order, lessons learned regarding: institutional setting, availability and access to information and science, robustness of civil society, and economic and regulatory frameworks.

Table 2. Lessons learned from case studies across key governance elements.

Governance Elements	Lessons Learned
Institutional Setting	• Governing is often a thankless task, yet it requires popularity • Legislation does not always translate into implementation • Conflict resolution is central to groundwater governance • Sufficient funding is of the utmost significance for governance
Availability and Access to Information and Science	• Natural systems, social systems, and institutions all have been understudied and would benefit greatly from additional research • Trust is a necessary element for all research • Urbanized landscapes are critical components of groundwater governance
Robustness of Civil Society	• Equity is an essential ingredient of groundwater governance • Community-based governance requires deliberate, purposeful intention • Leaders can unite stakeholders
Economic and Regulatory Frameworks	• Economic incentives can be effective, but may sometimes yield unintended, even opposite results • "Indirect" management approaches may be suitable in certain settings, but they should be used cautiously • The effectiveness economic incentives as use-control mechanisms depends greatly on the system employed

4.1. Institutional Setting

Our review of what the case studies tell us about institutional issues suggests four observations: (a) governing is a thankless and often criticized task, yet paradoxically it requires popularity; (b) legislation does not translate to implementation; (c) conflict resolution is central to groundwater governance; and (d) sufficient funding is of the utmost significance for governance.

Members of the scientific community (and the authors of our case studies) have noted that the role of the government should transform from "resource supplier" to "resource custodian" [38]. However, the role of resource custodian is problematic for many reasons; in particular, it offers an uneasy fit for most government agencies. Water-users, for instance, often disdain or resist restrictions, while in democratic societies politicians intrinsically seek popular support to retain their offices. If by default government absents itself from the process, groundwater management typically suffers [31]. Where livelihoods depend on groundwater resources, as in many developing societies—which coincidentally need greater human and financial capacity—this tension complicates stewardship [14].

When governments do pass water laws, they may discover that lawmaking is easy; law enforcement is the chief challenge [14], particularly when such laws require a shift from open-access to regulated resource [33]. To function as intended, legislation should be accompanied by awareness-raising educational programs and enhanced stakeholder engagement [20].

Broad participation can be an effective antidote to the shortcomings of top-down legislation. For example, water conservation is more likely to occur when it stems from a bottom-up approach than when it is mandated but unenforced [20]. In a variation on this theme, in Rajasthan, we see an opposite phenomenon. There, groundwater recharge is occurring on a massive scale—even though it is deemed illegal [28,32].

Whether dealt with top-down or bottom-up, water problems are primarily socioeconomic and political in nature and therefore can engender potential conflict over a precious commodity. For this reason, it is important to include conflict-resolution techniques in groundwater management. Van den Broek and Brown (2015) [31] found that social divisions based on wealth and education are not easily overcome during participatory processes. Innovative, context-specific conflict-resolution techniques can help alleviate struggles inherent in water-management processes [29]. One approach cited in our case studies is to employ social-science-trained experts as intermediaries [33,34].

An overarching need is captured in a common dictum: "No funding, no governance". Insufficient financing forecloses opportunities for technical services, infrastructure development, use of bottom-up approaches, capacity building efforts, and coordination of initiatives [20]. Moreover, it can corrupt water agencies [34]. Other products of lack of funds include dearth of trained personnel [3], and paucity of scientific knowledge [20], and too few social scientists to facilitate stakeholder engagement and deal with conflict resolution [33]. All these factors impede groundwater governance.

4.2. Availability and Access to Information and Science

The 10 case studies point to three lessons around the availability and access to data, information, and science: (a) natural systems, social systems, and institutions all have been understudied and would benefit greatly from additional research; (b) trust is a necessary element for all research; and (c) urbanized landscapes are critical components of groundwater governance.

Natural systems, which may have the richest research base, nevertheless could use additional exploration. There are needs for basic hydrologic data [29] to monitor quality and quantity of groundwater resources. Relating groundwater to other sectors and to ecosystem services also requires additional information and study [20].

Studies increasingly have demonstrated that socioeconomic factors are a primary cause of environmental problems, more so than natural factors [29]. Yet the role and significance of social systems in groundwater governance remains poorly appreciated and requires further study [14].

Demographic forces, for example, are critical to groundwater management because resource use is directly related to population [30].

Finally, the place and function of institutions, which serve as the backbone of governance processes, are incompletely understood. Robust research on their role would measurably improve governance capacity [14].

In all of this, trust comprises an essential element of research. When government conducts or sponsors research, there is evidence that communities may be skeptical, suspicious, or even hostile—especially when such research explores the feasibility of development projects [34]. The co-production of knowledge—i.e., involving a local community in a research project—is widely recommended [7,28,39].

Urbanized landscapes, which are proliferating in the face of population shifts to cities and megacities, are sites for land-use changes that affect hydrologic processes as well as major users of groundwater. As a result, municipalities are becoming increasingly important agents of governance. Simultaneously, developers are becoming key players because they have the power to contribute to water conservation or to resist it. In one Indian region, for instance, developers played a large role by installing water-harvesting systems in their buildings and have helped propagate the national water-conservation movement in India [28]. However, in Costa Rica, by contrast, the economic power of large development interests corrupted water agencies, authorizing new, groundwater-dependent development even under water-scarce conditions [34].

Whether in village settings or in large urban agglomerations, multi-participatory, multi-sectoral regional planning appears to be the soundest way to assure community needs and implement sustainable practices—not only for groundwater governance, but for resources governance more generally.

4.3. Robustness of Civil Society

Three observations related to robust civil society emerge from our review: (a) equity is an essential ingredient of groundwater governance; (b) community-based governance requires intention; and (c) forceful, effective, and progressive leaders can unite stakeholders.

Equity is critical to sustainable water governance [34]. Access to resources nearly always is accompanied by equity issues. In some instances, wealthy landowners can afford to dig deeper wells and exploit restored groundwater resources, while poor farmers cannot do so. Further, equity should include gender issues because water availability directly affects women and their potential participation in other activities, including water management. When water levels were restored in areas in India, women became able to access water with simple water pumps. This allowed them more time to engage in productive activities rather than spending their day foraging for water [32].

Equity issues also can relate to transparency in governance. On the one hand, transparency around behavior and water use can trigger debate on ethical issues regarding private information. Some might argue that personal-information disclosure infringes individual liberty [33]. On the other hand, lack of transparency (self-monitoring) can sometimes cause a "climate of suspicion" that can generate social tension [33]. In Costa Rica, insufficient transparency in development planning was related to water conflicts because it promoted a loss of credibility: community members do not believe enough water exists to serve future development [34].

Ethical values in natural-resource management can serve to promote civil-society engagement [28]. Yet, implementing or executing principles of "human solidarity" in practice is often seen to be difficult [29]. So too are mitigating social divisions based on wealth and education in stakeholder participatory processes [31].

It has become widely accepted that a community-based governance approach is central to groundwater governance, but it requires deliberate, purposeful intention. Community-based governance needs to be initiated from the outset [29] and requires legal status [31]. Many examples of community-based management have been seen as relatively unsuccessful throughout the world, with a few successful cases [14]. Success is tied to intention around the purpose and legal basis of the governance mode, but it is also linked to the focus of the governance in terms of supply and demand. Soft-path approaches are generally gaining acceptance and these tend to favor demand-management strategies that are viewed as more sustainable than supply-side ones. However, in some instances, successes have been attributed to supply-side schemes. For example, community-based initiatives aimed at supply augmentation can appeal to stakeholders and raise engagement because the conversation is not so narrowly focused on the burdens of limiting water use [14].

Finally, an emerging lesson from the cases is the role of leaders in uniting diverse participants in governance. Leadership is necessary to initiate action and acquire funding [32]. Committed leaders can unite community members by integrating traditional knowledge [32], and also by embracing ethics and where appropriate, spirituality. They can empower and inspire people for action [28]. Flexibility, trustworthiness, and communication are considered critical leadership skills for effective civil-society engagement in groundwater governance [20].

4.4. Economic and Regulatory Frameworks

Economic and financial practices, pricing policies, and regulatory policies vary substantially across the globe and that characteristic certainly is manifest in our case studies. Nonetheless, we do find three common strands: (a) economic incentives can be effective, though at other times they may provide unintended, even opposite results; (b) "indirect" management approaches may be suitable in certain settings, but they should be used cautiously; and (c) the effectiveness of economic incentives as use-control mechanisms depends greatly on the system employed.

Llamas and Garrido (2007) [29] provide an example of such perverse outcome by examining subsidies in Spain. These actions stopped neither the drilling of illegal wells, nor their pumpage. Likewise, in India, subsidies delayed some communities' participation in a well-recharge movement [28]. In France, paying penalties encouraged farmers to feel they have a right to exceed their water allocations [33].

At a larger scale, changes to the economic framework through "indirect" management—i.e., management of water resources via other sectors such as energy, food, and trade—can be problematic [14]. For example, the Indian government tried to reduce groundwater pumpage by implementing bans to electric supply, but new political candidates promised the exact opposite mechanism: electric connections for water-users [28]. Still, not all indirect management necessarily fails. In Mexico, for instance, substantial electric subsidies have effectively incentivized well-owners to register their wells [14].

Changes to governance regimes that move from a no-pricing to a pricing system may be met by resistance. This is not surprising: no one is eager to pay for something they previously have had for free. The Uganda case shows that people believe that water should be free of charge, therefore they refused to pay for the operation and maintenance of community-owned water pumps [31].

There is a role for market mechanisms in water governance systems, but with oversight. Without such oversight, water markets can promote agricultural expansion and growth beyond the carrying capacity of aquifers [28]. Alternatively, such practices can lead to water-use changes that do not necessarily decrease demand [30]. In other instances, insufficient oversight could result in resource depletion, particularly in arid lands [14]. In Arizona, where groundwater regulation is relatively strong, emerging water markets have shown successful results [27].

Our review suggests that the effectiveness of groundwater-use control via economic incentives depends on the particular system of incentives and enforcement and its relevance to and viability within its context. Because not all societies possess the financial and human capacity to enforce compliance with economic instruments, this sort of governance strategy is highly context-specific and should be used conservatively, lest it lead to unintended results.

5. Conclusions

There is growing recognition within policy circles and in academic scholarship of the importance of groundwater governance. To better understand lessons in groundwater governance around the world today, we reviewed and analyzed carefully 10 selected groundwater-governance case studies representing diverse regions. The cases provide a wealth of experience and observations, draw cogent conclusions, and offer potentially useful recommendations. We integrated and synthesized across the cases to distill key lessons on what animates actual, on-the-ground governance. We approached the case studies through the lens of four practical elements (or action steps) of governance employed in an earlier thematic paper on global groundwater governance and policy [3]. These elements—institutional setting, availability and access to information and science, robustness of civil society, and economic and regulatory frameworks—are seen as instrumental to groundwater governance and policy [3].

In terms of institutional setting, we found that: governing is a trying and usually unappreciated task, yet it requires popular support; legislation does not automatically translate to implementation; and that sufficient and reliable funding is essential for governance. Lemos and Agrawal (2006) [6] and other scholars within the broader environmental governance community frequently speak to the importance of implementation and funding.

Regarding availability and access to information, the cases highlighted the need for research on natural systems, social systems, and institutions; trust is an essential element for all research; and urbanized landscapes are becoming critical components of groundwater governance. This observation was confirmed by water-governance research concerning surface water (e.g., [40–42]).

Apropos the robustness of civil society, we learned that equity is an indispensable element of governance; community-based governance requires planned, purposeful intention; and leaders can unite stakeholders. This view of stakeholder engagement and participatory processes to support the engagement of diverse stakeholders is echoed and well-articulated in water-governance literature (e.g., [22,38,43,44]). Knowledge co-production processes are increasingly seen as important in not just building products—but building relationships between stakeholders [45].

Finally, in terms of economic and regulatory frameworks, the case studies illustrate how economic incentives sometimes provide unintended results; "indirect" management should be used with caution; and the effectiveness of economic incentives depends on the system employed. These reflections are perhaps less commonly found in western, non-Marxist economic literature, which tends to favor market-based approaches while discounting such factors as context and difficult-to-value commodities such as streamflow and aquifer storage.

Of course, many of these findings are not unique to groundwater *per se*. In their review of conditions to support effective science–policy interaction in transboundary river basins, Armitage et al. (2015) [46] conclude that the social and institutional context in which actors create and utilize scientific knowledge is fundamental. Increasingly, a number of water scholars are calling for greater attention to issues of democratization, equity, and human welfare in water governance (e.g., [47–52]). Strands of collaborative-governance research in public policy fields and studies of adaptive capacity well articulate issues of participation, knowledge and learning, leadership, and resources in governance (for a review, see [53]).

In addition, there exist common groundwater governance challenges that are not well articulated in the case studies reviewed here; some of these are nonetheless important issues related to governance. In terms of participation, the cases did not really engage in limits to participation or failed strategies to participation which may in part heighten the promotion of participatory approaches as a panacea to water governance [54]. Particularly in the cases of developing countries and communities associated with disenfranchised and poor citizens, participation may be implemented in inequitable ways that do not well certain segments of a population fairly. Redistribution of power and resources may be needed to engage the poor and achieve substantive stakeholder participation [55]. In terms of availability and access to information and science, there is little attention in the case studies reviewed here that speaks to the communication of information and data to decision-makers and the complexities of adaptive governance and the science-policy interface in water governance (e.g., [56–58]).

Collectively, the lessons drawn from our case-study analysis suggest a need for dual governance capacities—on the part of governments at multiple levels as well as civil-society actors. As any other common pool resource, groundwater faces challenges of overexploitation and protection [58]. Good policy design (even if we can agree on what this ought to entail) alone is insufficient for effective groundwater governance. Rather, implementation requires sufficient investments, reliable science, good leadership, and equitable decision-making. Even then—as real-world experiences show—unanticipated and often undesirable and costly consequences can result.

In spite of a number of observed commonalities, our review emphasizes that contextual considerations—i.e., locational, temporal, sociocultural, and procedural—are primary determinants of governance policies. There is no universal toolkit for groundwater governance, so communities will need to learn from each other. Additionally, in this regard, the growing body of case study research on groundwater governance will do well to address some of the heretofore unexplored or insufficiently addressed aspects of the subject including challenges of participation, intra-community equity, and legitimacy of leadership. Finally, we believe that decision-makers, stakeholders, and the public at large can benefit from integrated reviews such as this one to experiment with groundwater strategies and approaches that best suit their particular conditions, needs, and expectations.

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Abbreviations

The following abbreviations are used in this manuscript:

ADWR	Arizona Department of Water Resources
AMA	Active Management Areas
CAP	Central Arizona Project
CBM	Community Based Management
GEF	Global Environment Facility
GMA	Groundwater Management Act
OECD	Organization for Economic Co-operation and Development
TBS	Tarun Bharat Sangh

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