The Economics of Groundwater Governance Institutions Across the Globe

Eric C. Edwards, Todd Guilfoos

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The Economics of Groundwater Governance Institutions Across the Globe

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Eric C. Edwards[1]
Department of Agricultural and Resource Economics
North Carolina State University

Todd Guilfoos
Department of Environmental and Natural Resource Economics
University of Rhode Island

This article provides an economic framework for understanding the emergence and purpose of groundwater governance across the globe. Efforts to reduce common pool losses in the world's aquifers are driven by water scarcity, with problematic water table drawdown occurring in areas with low water supply or high demand. Drawdown creates local externality problems that can be addressed through a variety of management approaches that vary in the level of control over the resource and costs of implementation. We examine 10 basins located on six continents which vary in terms of intensity and type of water demand, hydrogeological properties, climate, and social and institutional traditions via an integrated assessment along three dimensions: characteristics of the groundwater resource; externalities present; and governance institutions. Groundwater governance is shown to address local externalities to balance the benefits of reducing common pool losses with the costs of doing so. In many basins facing drawdown, the high cost of coordinating large-scale governance institutions has resulted in a de facto state of open access resource use. However, the spatially local nature of externality problems allows for effective local management actions in some cases.

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1. Introduction:

Groundwater aquifers supply drinking water to approximately 1.5 billion people across the globe (Alley et al. 2002) and provide 43% of the total water consumed in agricultural irrigation (Siebert et al. 2010). The depletion of the world's groundwater systems in the largest irrigating countries—India, China, and the United States—threatens the sustainability of the world's food supply (Aeschbach-Hertig and Gleeson, 2012). Collateral effects of aquifer drawdown include problems such as land subsidence and seawater intrusion. Severe cases of subsidence are found in Mexico City, Bangkok, Shanghai, and California's Central Valley, permanently reducing water storage with measured declines in land elevation of tens of meters in some cases (Konikow and Kendy, 2005). Seawater intrusion reduces the availability of freshwater to coastal populations and can render drinking water supplies unfit for use, with severe cases in Oman and California (Zekri, 2008; Barlow and Reichard, 2010).

Despite the high costs of continued overexploitation, successful groundwater governance has been elusive in many regions. The world's aquifers remain largely open-access resources, with overlying landowners free to pump water subject to few restrictions. Efforts to understand the economic factors underlying groundwater governance, including where it emerges, its form and function, and its successes and challenges, remains largely absent from the literature. This is despite the fact that increased monitoring of groundwater pumping and the use of geographical information systems and remote sensing have allowed for significant advances in the type of empirical methods available to researchers studying groundwater. We know a great deal about groundwater physical processes and interactions with human behavior, but how to translate this knowledge into solutions is less clear. For this paper, we define *governance* to be institutions that guide behavior and *management* as decisive action by an organization to improve water management. We utilize an economic framework to help explain the emergence, purpose, and challenges of groundwater governance across the globe.

Why does full groundwater governance appear to be limited globally? The first explanation is supply and demand. Where water is abundant or people are scarce, issues with groundwater depletion are limited. Even by the most conservative measures of sustainability, 80% of the world's aquifers have recharge in excess of extraction (Gleeson et al. 2012). However, even where demand for water is large and supply is limited, groundwater governance is seemingly incomplete. This is the focus of our work. We examine 10 basins located on six continents which vary in terms of intensity and type of water demand, hydrogeological properties, climate, and social and institutional traditions via an integrated assessment along three dimensions: characteristics of the groundwater resource; externality problems; and governance institutions. Our framework suggests that the coordination required to limit aquifer depletion is costly, and these costs limit the completeness of the solution that is ultimately implemented (Demsetz

1967; Libecap 1989; Ayers et al 2018). However, the spatially local nature of groundwater externality problems allows for effective local management actions in some cases.

2. Background

Groundwater users share a finite, but often renewable, amount of water such that each pumper's use can reduce the water available to neighboring wells, decreasing future availability and increasing pumping costs. Under open access, pumpers do not fully own the water and thus do not consider the full opportunity cost of applying it to a different purpose or at a different time (Provencher and Burt 1993). When overlying landowners drill wells to access groundwater, their pumping creates local areas of drawdown, pulling water from the surrounding formation (Bredehoeft et al., 1982; Brozovic et al., 2010; Guilfoos et al., 2013; Edwards, 2016).

If the rate of pumping is high enough, local areas of decline can reach bedrock; overlapping pumping effects can reduce or eliminate the flow of water to pumps (Peterson and Saak 2018; Merrill and Guilfoos 2017). Hydrogeological and human factors determine the magnitude of the cross-well effects. In addition to changing the availability of water in the present or future, excessive pumping can cause subsidence, permanently reducing storage capacities and disrupting cropland and other built infrastructure. Where basins border the ocean, excess pumping allows seawater to enter the groundwater formation, increasing treatment costs or rendering it unfit for human and agricultural use (Zekri, 2008; Barlow and Reichard, 2010).

Economic-hydrologic models help predict where institutional controls on extraction may be beneficial. The early groundwater economics models (Gisser and Sanchez, 1980) find benefits do not increase appreciably from collectively planned pumping, suggesting externalities are limited in a bathtub-like basin, accessed by many pumpers, and where pumping at one location is instantaneously transmitted to others. This model suggests that groundwater governance provides limited benefits (Gisser and Sanchez 1980) and, given the expense, is unlikely to be undertaken (Burness and Brill 2001). However, altering the assumptions of the hydro-economic model suggests that changing parameters or incorporating other externalities may make governance more valuable. For instance, changes in marginal pumping costs (Gisser and Sanchez, 1980; Guilfoos et al., 2013), exhaustion of groundwater (Merrill and Guilfoos, 2017), well capacity constraints (Manning and Suter, 2016; Foster et al., 2015; Foster et al., 2017), or ecologically valuable outflows (Esteban and Albiac 2011) all increase the expected gains of management.

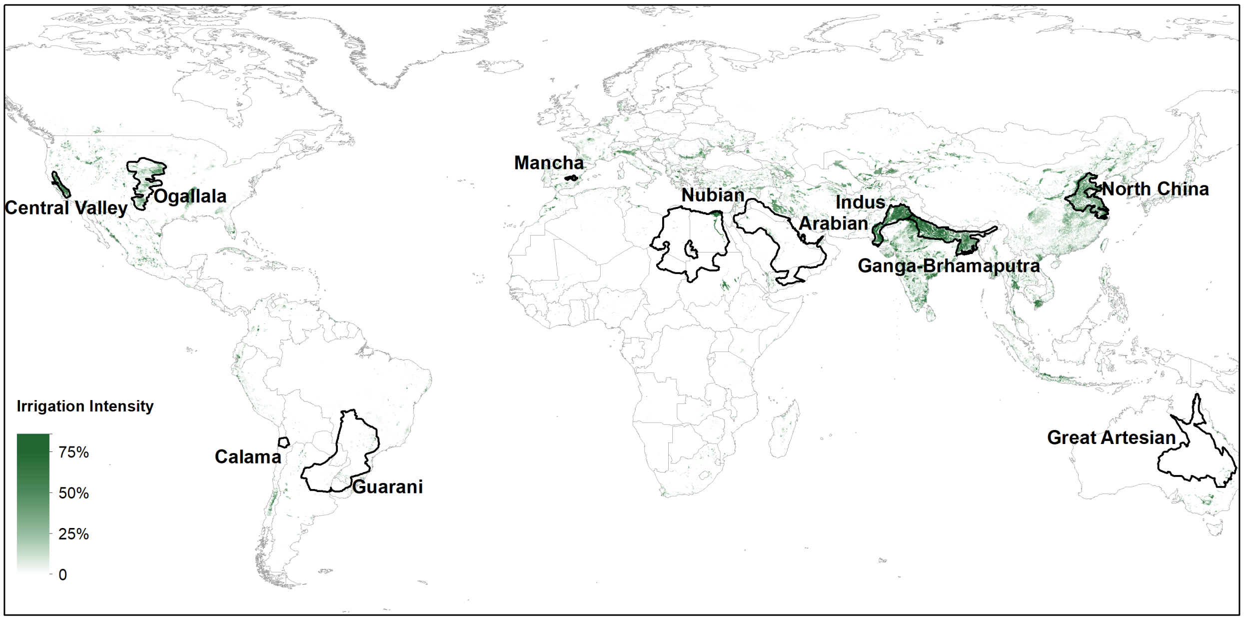
Darcy’s Law and the Theis Equation have been used to model lateral subsurface flows, and many economists have leveraged this modeling in their work (Saak and Peterson, 2007; Brozovic 2010; Guilfoos et al. 2013; Suter et al. 2012). Lin Lawell (2016) notes the recent shift in economic-hydrologic modeling to incorporate spatial work that addresses the complex relationship between groundwater users and the movement of groundwater. Koundouri et al. (2017) also highlight the importance of spatial analysis to groundwater economics, which incorporates heterogeneity in aquifers from well distributions, crop choices, or physical properties such as recharge, saturated thickness, or hydraulic conductivity. Not only is groundwater modeling important to economic questions of governance, but so are interactions with surface water and how to model conjunctive management (Tsur and Graham-Tomasi, 1991).

However, work translating modeled gains from coordinated pumping into an understanding of groundwater governance has been limited. In cases where resource heterogeneity creates varying local conditions and preferences, "national governmental agencies are frequently unsuccessful in their efforts to design effective and uniform sets of rules to regulate important common-pool resources across a broad domain. (Ostrom 1999, p.495)" Subsurface groundwater systems are complex and achieving first-best management outcomes is difficult, yet localized policies that are more efficient and garner more popular support may provide politically-feasible second-best solutions (Guilfoos et al. 2016; Edwards 2016). Thus, we pay attention to both broad, basin-wide trends in groundwater governance as well as local solutions to manage the groundwater commons.

The primary issue in groundwater depletion is human behavior, not geophysical processes. Collective action to address depletion in the use of groundwater depends on people and how they view their incentives. Groundwater provides two challenging issues to incentivize cooperative behavior in conserving water. First, the impacts of pumping and external costs to others are generally unknown or difficult to ascertain. Second, the majority of benefits in conserving a depleted aquifer accrue in the future, and therefore the incentives are stacked against cooperative action in the present. Without institutions to help with economic incentives, human behavior in an open-access resource will often lead to myopic behavior (Ostrom et al., 1992; Walker and Gardner, 1992; Ostrom et al., 1994). It is also possible that groundwater pumpers behave strategically (Pfeiffer and Lin, 2012; Liu et al. 2014), although more evidence is needed to support this claim. A game-theoretic model of pumping behavior does not seem to comport with behavior in a lab where information is more easily available and stochastic processes can be controlled (Suter et al. 2012). We assume that open access conditions incentivize myopic behavior in the following sections.

We focus our analysis on broadly defined aquifer systems across six continents, as shown in figure 1. For the remainder of the paper we combine the adjacent but hydrogeologically separated Indus and Ganga-Brahmaputra basins due to their similarity in geography, hydrologic properties, and governance issues, leaving us with 10 basins for analysis. We chose these systems to provide a diverse cross-section of locations, hydrogeological properties, and governance regimes, while including some of the world's largest systems in the most water-scarce areas and those systems most important to irrigated agricultural production, the primary use of groundwater worldwide. Section 3 provides an integrative framework for comparing the basins. Section 4 describes the 10 basins in detail and section 5 analyzes each basin based on our economic framework. In section 6, we then discuss the challenges to effective groundwater governance and how future research linking economic and hydrologic understanding could be important in solving these problems. Section 7 concludes.

Figure 1. Study groundwater basins and worldwide irrigation intensity



Source: Author's drawing using data from the Food and Agriculture Organization of the United Nations, UNESCO, the European Environment Agency, and ESRI.

3. Integrative framework

We provide a framework for our cross-country assessment by systematically evaluating groundwater governance across three key dimensions: the groundwater resource, externalities, and governance. Figure 2 shows a two-cell groundwater model that can incorporate the basic dynamics in economic/hydrologic models. The left panel depicts the physical setting symbolically represented in the right panel. It is easy to imagine expanding to more cells in the model to create a connected grid of cells, all with different users, and how externalities from pumping spread across the aquifer over time based on the hydrologic properties of the cells and pumping behavior.

In a model composed of parcels $i=1,2,\ldots,n$ overlying the groundwater basin, each user has a net benefit function from groundwater that includes the revenue earned and the costs of pumping. Equation 1 gives the net benefit function for farmer i across the projected life of the aquifer (T).

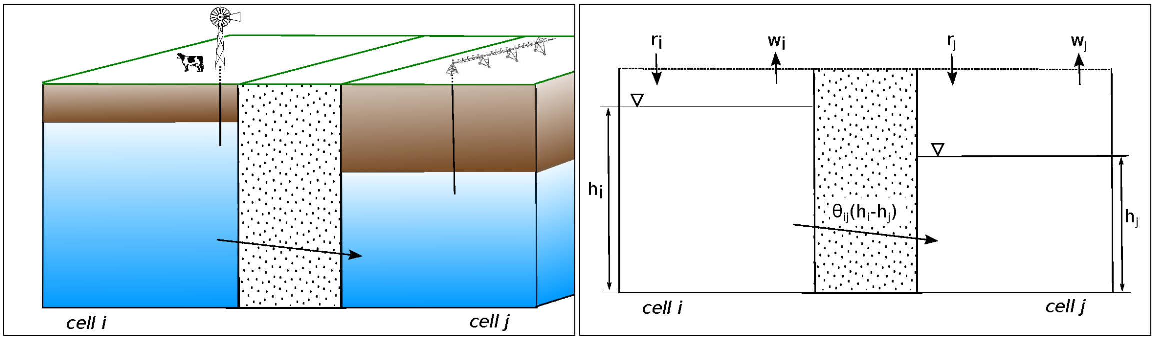
$$NB_i(w_i, h_i) = \int_0^T \pi_i(w_i, h_i) e^{-\delta t} dt \qquad (1)$$

Net benefits are an increasing function of groundwater pumped, w, and the elevation of the groundwater, h. We suppress the time subscripts for simplicity. More water pumped results in greater revenues, although marginal revenue may be declining. A higher water table elevation decreases the pumping distance and costs. Since groundwater extracted from the aquifer by all users affects the future state of groundwater resources, we describe the change in elevation in equation 2, the state equation:

$$\dot{h}_i = r_i - w_i - \theta(h_i - h_{-i}) \qquad (2)$$

The state equation shows how recharge, r, groundwater extracted, w, and inter-parcel transfers of water determine the change in elevation under any user's parcel. The flow of groundwater is determined by the elevation differential of groundwater levels at neighboring parcels, $h_i - h_{-i}$, and the volume of transfer is determined by the properties of the soil and saturated thickness of the aquifer at the parcel, which is captured by the coefficient θ.

Figure 2. Two-cell groundwater model with two users



A. Groundwater Resource

The extent and geophysical parameters of groundwater basins vary widely across the world. To get a sense of the differences between basins we look at the key geophysical and economic variables from equations (1) and (2).

Recharge

The supply of water available for extraction in each groundwater basin is defined by the existing stock of water deposited and the annual influx of recharge, r. More precipitation is generally linked to greater recharge, but surface water sources may move additional water into or out of a groundwater basin via natural or human systems. Groundwater basins are differentiated based on their natural recharge. Basins that accumulate negligible amounts of natural recharge are considered non-renewable resources and extraction resembles mining. Basins that receive non-negligible amounts of natural recharge are renewable resources, but groundwater mining can occur where extraction exceeds recharge. Considerable heterogeneity exists between the amount of recharge within and across basins. Within basins, recharge can occur in one area and then flow to another, such as occurs in the Calama Basin in Chile. Different portions of an aquifer can be considered renewable and non-renewable. Some areas of the Ogallala (Nebraska) receive sufficient recharge to be considered renewable, while other areas (Oklahoma, Texas) are essentially non-renewable.

Lateral flows

How groundwater moves through the ground is defined by the hydraulic conductivity of an aquifer, which along with cross-sectional area defines θ. Conductivity is determined by the type of soil that water is moving through and the permeability of that soil. The major types of aquifers are 1) sand and gravel 2) sandstone 3) karst 4) volcanic and 5) basement. The large groundwater systems we investigate here often include multiple types of sediment. Sand and gravel aquifer systems characterize the most common of the exploited systems and have high porosity and permeability, which lead to greater flow velocities for groundwater.

Groundwater elevation

The elevation of groundwater is determined dynamically by the amount of stock existing from prior precipitation, current recharge into and flows out of the aquifer, and anthropogenic extractions. Groundwater systems are either confined or unconfined. Confined aquifers, such as the Great Artesian Aquifer in Australia, have impermeable layers that keep the aquifer pressurized, and when pierced by a well creates a water table level higher than the upper layer of the aquifer. Unconfined aquifers have a water table that is at atmospheric pressure and is more likely to be connected to surface water. Groundwater systems can maintain surface flows during dry times of the year and greatly affect water supply downstream contingent on groundwater pumping activity. Heavy extraction of groundwater may reduce baseflow in streams when ground and surface water are connected. This is the mechanism for how groundwater extraction can affect water users far downstream.

Groundwater elevation is seasonal in many aquifers for two critical reasons. First, in groundwater basins which are connected to river systems, such as the Indus and Ganges basins, surface water flows affect groundwater elevation. In the dry season the supply may become limited because the depth to groundwater is too deep for shallow wells to reach. This is a reoccurring problem in Bangladesh (Qureshi et al., 2014). Second, the seasonal pumping of water creates cones of depressions around high producing wells that can interfere with neighboring wells. The drop in the water table either limits production at neighboring wells or runs them completely dry during irrigation season, and a rebound effect in the water table is delayed based on the conductivity of the aquifer.

Extraction

Demand for groundwater is characterized by the type of economic activity the water is put to, and along with the cost of pumping, determines the amount of extraction, w. Water demand is typically broken into irrigation, manufacturing and industrial, and public supply (drinking water). In many of the aquifers explored in this paper, depletion occurs most severely due to irrigation demand. Depletion is the broad measure of demand for water used in cross country studies. However, depletion is not an explicit economic value of water but rather a state of physical depletion.

B. Externalities

Many externalities affect the world's groundwater basins, with marginal damage functions that differ in magnitude and shape. However, we can generalize that the external cost is increasing in groundwater depletion. Thus, we modify the model to include an externality term, $E(\cdot)$ that is a decreasing function of the elevation of the groundwater table:

$$NB_i(w_i, h_i) = \int_0^T [\pi_i(w_i, h_i) - E_i(h_i)] e^{-\delta t} dt \qquad (3)$$

Equation 3 explicitly separates externality costs from an individual user's pumping costs, although both costs are decreasing in *h*. The equation of motion remains equation (2). Under open access conditions, a myopic pumper will ignore the effect of pumping on resource stock, causing aquifer drawdown and increasing the pumping cost in all future time periods for nearby wells; as well as decreasing the availability of water to buffer fluctuations in precipitation. These externalities are referred to as the *pumping cost* and the *risk* externalities, respectively. The reduction in stock also has the potential to cause issues considerably costlier than the two externalities mentioned above, depending on local conditions. We focus on six other externalities: (i) loss of *artesian pressure*; (ii) depletion of *surface flows*; (iii) land *subsidence*; (iv) local areas of *rapid drawdown*; (v) *bedrock interactions*; (vi) *seawater intrusion*.[2] The externality function $E(\cdot)$ maps groundwater elevation to the total economic cost of these six externalities. Figure 3 provides a detailed explanation of these six externalities.

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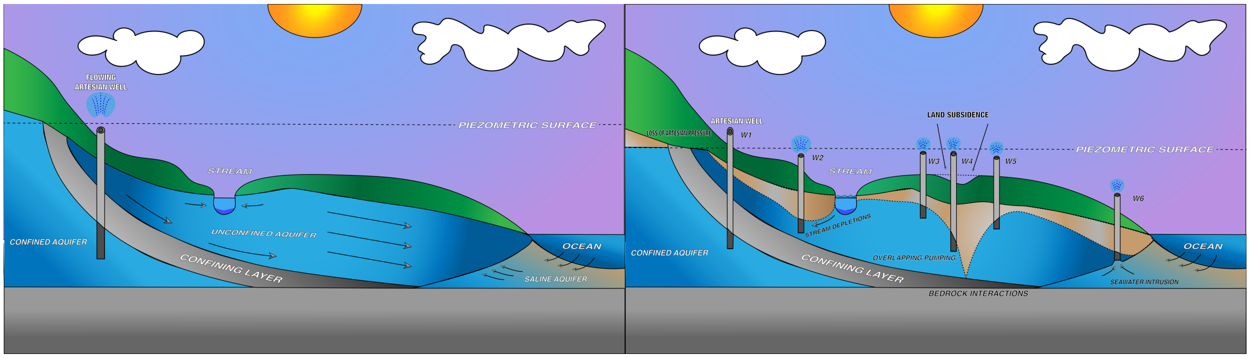
[2] Other externalities, water quality issues and pollution from overland activities, are excluded primarily for brevity and simplicity and are seen by the authors a secondary to the six externalities listed in the text.

Figure 3. Diagram of groundwater pumping externalities



Notes: The left panel shows the natural groundwater system without pumping. Groundwater elevation and baseflow to a stream are in equilibrium. (While the natural system is likely to be in flux within a season and over time as conditions change, a static equilibrium allows for clearer illustration of groundwater extraction externalities.) A confined aquifer provides subsurface pressure for a free-flowing artesian well below the piezometric surface, while the stock of fresh groundwater prevents the saltwater aquifer from moving inland. When pumping begins, the reduction in the elevation of the confined aquifer lowers the elevation of the piezometric surface, reducing or eliminating the artesian pressure in the well (W_1). Pumping creates a cone of depression (W_2) which lowers the water table in the immediate vicinity of a stream, reducing surface flows. When several wells are located in close proximity, (W_3, W_4, W_5) they create overlapping cones of depression and areas of rapid depletion. Land subsidence occurs when high density pumping results in aquifer drawdown, causing the potentially permanent compaction of aquifer rock and sediments, lowering surface elevation, and damaging infrastructure. Additionally, rapid pumping can cause water tables near a well to decline to the point where they interact with bedrock, or otherwise become too deep for economical extraction (for instance when high-intensity seasonal agricultural water use causes shallow wells to go dry). Pumping near the coast (W_6) can break the natural barrier freshwater aquifers provide, leading to costly brackish water intrusions into coastal wells.

C. Governance

As in many common-pool settings, establishing effective governance institutions to solve the problems of open access are costly. Complete property rights to groundwater are seldom defined because of high measurement and bounding costs (Burness and Brill 2001). Less costly and less complete solutions include requiring pumping permits, retiring pumping rights, and closing areas to new wells. Because these controls are costly their implementation will evolve as the benefits of more secure control of the resource increase (Demsetz 1967). Groundwater basins are conducive to successful collective management because they generally have well-defined boundaries with a limited and relatively stable group of overlying landowners who may already engage in other repeated cooperative actions above ground (Ostrom 1990, p.90).

Whether a basin engages in collective management is determined by the size of expected gains; number of bargaining parties; heterogeneity of bargaining parties; information on the resource and its value; and the concentration or skewness of the allocation system. (Libecap 1993, p. 21). Models of market failure in groundwater extraction suggest different groundwater basins observe different levels of potential gains, and the collective action literature suggests additional factors influencing potential outcomes (Ayres et al.

2018). The number and variety of groundwater management approaches that have been implemented in the US suggest a wide variety of management options. Often, groundwater management institutions have emerged as a result of user initiatives—collective action—rather than top-down regulation. Observed management measures include well-spacing and area closure rules (Edwards 2016); pumping taxes (Smith et al. 2017); market exchanges (Kuwayama and Brozovic 2013); and user-initiated pumping restrictions (Drysdale and Hendricks 2018).

Our framework for understanding groundwater governance is one of net benefits and transactions costs (Ayres et al. 2018). More stringent controls are observed when the value of the resource is high or with lower costs of bounding, monitoring, and enforcement of rules on extraction or use (Demsetz 1967). Transaction costs, which are the costs of defining, enforcing, and trading property rights (Coase 1960, Allen 2011) can render beneficial controls too expensive on net. To formalize this process, assume users can undertake a policy that protects the water table by conserving some amount of water for each portion of the aquifer, relative to open-access drawdown. Each user bears a cost of this policy of κ_i. The new conservation pumping path is ω_i, where $\omega_i \leq w_i$, and as a result $\eta_i \geq h_i$ for each user. Each user sees net benefits from the new regime if:

$$[NB_i(\omega_i, \eta_i) - \kappa_i] \geq NB_i(w_i, h_i) \qquad (4)$$

As individual external costs increase, so do the benefits of the conservation pumping path increase, but the inequality is less likely to be satisfied as transaction costs, κ, are increasing. In aggregate, the benefits of the policy are positive when:

$$\sum_i [NB_i(\omega_i, \eta_i) - \kappa_i] \geq \sum_i NB_i(w_i, h_i) \qquad (5)$$

Conservation policies where the inequality in equation (5) is satisfied do not necessarily satisfy the inequalities in (4) for all users, or at least these users' perceptions of (4). Therefore, the distribution (and perceived distribution) of the benefits and costs of potential management approaches determines how difficult implementation will be. Satisfying the inequality of equation (5) is not sufficient to guarantee collective action as other aspects of social choice can be important, like fairness. The process of groundwater governance involves comparing management strategies on both their benefits and barriers to implementation—transaction costs. Formal modeling of this process is difficult because of the level of specificity required to understand policy alternatives and their translation to individuals' perceptions of benefits and costs, as well as the endogeneity of the process itself. Ostrom (1990) suggests that the governance process itself determines in part the benefits and costs. For instance, the involvement of stakeholders in developing institutions is critical to promote prosocial behavior and to get buy-in from the people that they are designed to govern.

Because of the importance of benefits and costs to effective governance, the spatial nature of groundwater externalities is crucial in understanding observed institutional response. Spatial externalities mean problems are typically localized; creating local solutions reduces the number (and likely heterogeneity) of users who need to coordinate on a solution. However, spatial externalities can increase transaction costs where they create heterogeneous effects. For instance, seawater intrusion near Monterey, CA created divergence in the incentives to strictly regulate benefits (pumpers near ocean) and costs of reducing pumping (all users). Inland farms not affected by seawater intrusion refused to join coastal users in limiting pumping to protect coastal drinking water supplies (Ayres et al 2018). Spatial effects can also create complexities that hinder effective management. For example, to address surface depletion externalities, limiting groundwater pumping near the stream or river is effective. In Nebraska, groundwater trading to account for these dynamics required a more complex management approach to account for differences in the transmittance of pumping effects, but this spatial heterogeneity also increased the benefits of more secure institutions and transferable water rights, relative to uniform basin-wide management approaches (Kuwayama and Brozović 2013; Brozović and Young 2014).

In our study, governance options focus on management rules limiting the permitting, drilling, and extraction of water from a well. Groundwater management has a complex set of costs and benefits, and in different settings benefits, costs, and the transactions costs differ. The benefits of controlling groundwater extraction are generally increasing in the value of the resource, as are the transaction costs of adopting a management regime. However, the rate by which costs and benefits change are not constant across management strategies, and may differ significantly across basins. Still, we can group certain management approaches into tiers based on empirical observation, as shown in table 1. Effective management actions require coordination, but the driver of these actions could be top-down, imposed by a state or national government, or bottom-up, proposed and implemented by users themselves.

Generally, the benefits and transaction costs of management approaches are increasing as tiers increase. Tier I represents a variety of limited management regimes that resemble open access conditions. Overlying landowners are allowed to pump, generally without binding limits, through a de facto property right, although whether there is a de jure property right to do so, or just a lack of regulation or enforcement, is not specified. Tier II includes measures that require small decreases in users' ability to access the water resource freely, but will generally not affect existing users or provide a binding cap on individual well extraction rates. This tier includes the formation of an entity to study the problem of groundwater drawdown; requirements for permits or entitlements to drill a well, typically providing a corresponding database of well locations; and may include spacing restrictions on wells. Tier III includes more significant measures, especially rules to issue uniform cutbacks on pumping; require individual users to monitor their pumping; allow certain wells to be retired from use; restrict or close the issuance of drilling permits in sensitive areas or those considered overdrawn; and implement recharge into the groundwater basin. Tier III approaches are generally characterized by limiting the ability of new pumpers from drilling wells, while allowing current pumpers continued flexibility in pumping. Tier IV includes more significant individual regulation of pumpers, including binding caps on pumping and rule enforcement. Tier V includes the most complete tracking of water which, although expensive, aligns user decisions most fully with the opportunity cost of the water. Groundwater markets and banking account for each user's rights to water, either rights to pump or rights to stored water, and allow transfers between users.

The proposed tiers are classifications of greater control, potential benefits, and transaction costs and do not represent progressive effective governance. Local governance choices will depend on the local benefits and costs of action which may be optimal at a lower tier.

Table 1. Tiers of Groundwater Governance

Progression	Description	Evaluative Literature
Tier I		
Open access	Few or no limitation on pumping by overlying landowners/users	Kanazawa (1992)
Tier II		
Management entity formation	Formation of districts, councils, etc. to promote conservation, define scope of problem, advocate for policy	Edwards (2016); Ayres et al (2018); Nachbaur (2007)
Well permits/entitlements	Control of right to drill and maintenance of well database	Guilfoos et al. (2016)
Well spacing	Minimum distance requirements for new wells	Edwards (2016)
Tier III		
Area closure rules	Stop issuance of permits for specific regions	Edwards (2016)
Well monitoring requirements	Mandatory metering of wells	Babbitt et al. (2018)
Well retirement	Removal of wells from production	Tsvetanov and Earnhardt (Forthcoming)
Groundwater recharge	Investment for artificial replenishment	Harou and Lund (2008)
Local uniform rules	Cutbacks or pricing implemented uniformly	Smith et al. (2017); Drysdale and Hendricks (2018); Huang et al. (2013)
Tier IV		
Binding pumping caps	Limits on total basin extraction and assignment of individual pumping caps	Ayers et al. (2018); Ayers et al (2019)
Punitive rule enforcement	Monetary or other penalty for excessive withdrawals	Halder (2019); CA Water Code 100732
Tier V		
Groundwater banking	Storage and ownership of recharged groundwater	Guilfoos et al. 2016
Groundwater markets	Transfer of pumping rights	Kuwayama and Brozović, (2013); Brozović and Young, (2014); Edwards et al (2018); Wheeler et al. (2016); Manjunatha et al. (2011)

4. Background on Study Basins

We apply our integrated framework to groundwater governance issues in the following basins: The Indus and Ganges-Brahmaputra Aquifers, North China Plain Aquifer, Calama Basin Aquifer System, Guarani Aquifer System, Arabian Aquifer System, Nubian Aquifer System, Mancha Aquifers, Great Artesian Aquifer, High Plains Aquifer, and Central Valley Aquifer. Table 2 provides a summary of the basins, including the primary countries overlying the basins, basin area, and the maximum thickness of the water-bearing formation. Where available, we have also included measures of the cumulative volume of depletion of each aquifer and the time-period for which it is measured, and a measure of water footprint. The water footprint is "the area required to sustain groundwater use and groundwater-dependent ecosystem services," with measures >1 being those where an aquifer is currently being unsustainably exploited, i.e. it is being drawn down (Gleeson et al. 2012). We describe each basin below before turning to the integrated framework.

Indus and Ganges-Brahmaputra Aquifers

The Indus Aquifer in northwestern India and the Ganges-Brahmaputra Aquifer in northeastern India and northern Bangladesh are heavily exploited, primarily for agricultural irrigation. In India, there are few regulations on groundwater use and extraction costs are heavily subsidized. Some areas, like Rajasthan, have passed legislation that sets up a state groundwater authority, restricts tubewell development, and provides a framework for privatization, but corruption and a lack of trust by local farmers of state-run resources and institutions hinders success (Birkenholtz 2009). Bangladesh, like India, suffers from subsidies and cheap extraction costs and high levels of groundwater development with weak and underdeveloped management institutions (Qureshi et al 2014). Groundwater depletion has caused reduced surface flows in the Ganges-Brahmaputra basin causing concern in Bangladesh over disruptions to irrigation.

North China Plain Aquifer

The North China Plain Aquifer (NCPA) is located in a major floodplain and is extracted heavily for irrigation water. It contains confined layers below the unconfined layers and some areas of the aquifer accumulate significant recharge. The deep parts of the aquifer are confined and essentially receive no recharge, creating concerns about its development. Recently the use of double cropping in some areas has led to drops in groundwater levels of 1m per year (Yang et al. 2017). Depletion is leading to seawater intrusion near the coast and land subsidence further inland.

Calama Basin Aquifer System

The Calama aquifer is located within the Loa River water system in northern Chile's Antofagasta Desert and supplies a majority of the region's municipal, agricultural, and industrial water supply, including water to the region's mining industry, which supplies 17% of the entire world's copper (Edwards et al 2018; Cochilco 2014). Broadly, the system consists of an upper limestone and sandstone aquifer with a confining layer 80-200m below the surface and a confined conglomerate aquifer below, which allows for artesian wells in some locations (Jordan et al. 2015). The Antofagasta Desert is one of the driest areas in the world and it has been hypothesized that the upper aquifer is fed via groundwater flows from outside the basin while the lower aquifer may be a fossil water remaining from a wetter time-period (Houston and Hart, 2004). Due to high demand in mining, the opportunity cost of freshwater in the region is extremely high, with mining firms paying to desalinate and pump water to their mines when groundwater is unavailable.

Table 2. Long-Term Groundwater Depletion in Major Aquifers

Basin	Primary Countries	Extent (x 1,000 km^2)	Max Thickness (m)	Reference Period	Cumul. Depletion (km^3)	GF/A_A
Renewable						
Ogallala	United States	450	150	1900-2008	353	9.0
Central Valley, CA	United States	80	600	1900-2008	113	6.4
North China Plain	China	320	1,000	1900-2008	170	7.9
Northern India Systems	India, Pakistan, Nepal, Bangladesh	~920	600	1900-2008	1,361	18.4-54.2
Guarani	Argentina, Brazil, Uruguay, Paraguay	1,200	800	*	*	<1
Mancha Aquifers	Spain	12.76		Thru 2002	3.1	**
Calama	Chile	0.6-0.8	210	*	*	**
Non-Renewable						
Arabian Aquifer System	Saudi Arabia	>1,485	6,500	1900-2008	468	38.5-48.3
Nubian Aquifer System	Egypt, Libya, Sudan, Chad	2,176	3,500	1900-2008	98.4	**
Great Artesian Basin	Australia	1,700	3,000	1880-1973	25	<1

Notes: GF/A_A is a measure of groundwater stress based on the groundwater footprint over the area of extraction (Gleeson et al., 2012). Estimates are based on mean runs of data and ** are aquifers not classified, from Gleeson et al. (2012). *Cumulative depletion numbers are not available for Guarani and Calama Aquifers.

Sources: Margat and Van der Gun (2013), Konikow (2011), Foster and Loucks (2006, p.82), Esteban and Albiac (2011), and Jordan et al. (2015).

Guarani Aquifer System

The Guarani is one of the largest transboundary aquifer systems in the world, underlying parts of Argentina, Uruguay, Paraguay, and Brazil. The Guarani system has an immense stock of water, is not yet heavily exploited, and receives considerable recharge, making governance less pressing than for other systems. An international agreement on aquifer management was signed in 2010 between the four countries, but is limited in its scope and powers (Villar and Ribeiro 2011).

Arabian Aquifer System

The Arabian Aquifer System is a sandstone aquifer primarily underlying Saudi Arabia. Due to the arid climate it is non-renewable and has experienced heavy depletion due to agricultural development. This system of aquifers is likely the most dramatic case of depletion among our sample due to the low recharge and large-scale production of wheat in Saudi Arabia from the 1980s to the late 2000s. The intensive use of groundwater in this region is sponsored by Saudi Arabia through subsidies to help the country become more food secure, primarily focused on cereal production. This has led to a large loss in groundwater reserves (Elhadj, 2004) and a shift in water policies in recent years (Ouda, 2014). In Saudi Arabia, the loss of groundwater reserves is the primary externality, though pumping (Müller et al., 2017), water quality (Rehman and Cheema, 2016), and sea water intrusion also are important externalities in the region.

Nubian Aquifer System

The Nubian Aquifer System (NAS) is a sandstone aquifer in the Northeast of Africa over the Sudan, Egypt, and Libya. It is the largest fossil water aquifer in the world. The primary use for extracted groundwater is for irrigated agriculture. Total groundwater extracted in this aquifer system has increased greatly from the 1970s (Konikow, 2011). In some areas of the aquifer extraction has led to salination concerns and the low amount of recharge increases concerns about future groundwater availability for irrigation and drinking water. Oases and sabkhas and can be dried up by the extraction as discharge from the aquifer dwindles.

Great Artesian Aquifer

The Great Artesian Basin is a large aquifer in Australia stored in vast sandstone deposits and reemerging through springs to sustain communities, habitats, and industries. It is the largest artesian basin in the world and has faced increasing problems as more bore wells have been drilled, decreasing the discharge flow out of artesian wells. Often, the borehole wells are the only supply of water for farmers or towns. The growth of borehole wells has resulted in the diminishing of natural discharge with some natural springs drying up entirely (Habermehl, 2006).

High Plains Aquifer

The High Plains Aquifer in the central United States underlies portions of eight states and provides extensive irrigation water for crop production in Texas, Oklahoma, Kansas, and Nebraska. Governance institutions are at the state or local level and include well-spacing and area closure rules to address areas of rapid depletion (Edwards 2016); market exchanges to address stream depletion (Kuwayama and

Brozovic 2013); and uniform pumping reductions to address long-run overdraft (Drysdale and Hendricks 2018). The northern portion of the aquifer has high levels of recharge, while the southern portion is essentially nonrenewable, with rapid depletion and falling groundwater tables observed in parts of Kansas, Texas, and Oklahoma. As with most of the heavily irrigated areas around the world, the advent of the mechanical pumping and electrification of the area led to the precipitous increase in groundwater withdrawals. Pumping externalities, local exhaustion of stock, and depletion of surface flows are the primary externalities across the basin.

Central Valley Aquifer

The Central Valley Aquifer underlies all of California's Central Valley, one of the most productive agricultural regions in the world. The basin is somewhat unique relative to the others in this study in the large amount of imported water flowing into the basin via the State Water Project and Central Valley Project. Heavy exploitation of the aquifer as both a primary and supplementary water source for crop production, including high-value perennials, has created extensive drawdown and land subsidence. In 2010 some areas of the aquifer have shown subsidence of up to 10 inches per year (Jeanne et al. 2019).

Mancha Aquifers

The Mancha aquifers are two geographically adjacent aquifers in geologically distinct river basins. The Júcar River Basin in southeastern Spain contains 52 aquifers of which the Mancha-Oriental (MO) Aquifer is the largest (Apperl et al. 2015). It is one of the largest carbonate aquifers in the country and has significant interaction with the surface waters of the Júcar system. Immediately to the west, the Western Mancha Aquifer is the largest of four aquifers on the Upper Guadiana River Basin. The region is semi-arid and has seen a large increase in groundwater pumping since the 1970s as a result of the conversion from dryland to irrigated agriculture, which now accounts for around 90% of water withdrawals. Variable precipitation cycles since the 1970s have led southeastern Spanish aquifer extractions to draw down water tables in dry years (Apperl et al. 2015; Closas et al. 2017). The MO aquifer currently has withdrawals in excess of recharge (Apperl et al. 2015). The primary externalities associated with aquifer drawdown in Spain are the depletion of water for future supply, the impairment of surface flows, and reduced pressure in artesian wells.

5. Cross-Country Comparison

Table 3 provides an economic comparison of the 10 aquifer systems in our study. The table is partially incomplete due to missing data. For each aquifer we compute the ratio of extraction to recharge as a measure of the extent to which the aquifer is being mined. The Arabian Aquifer has minor amounts of recharge, and thus a high ratio, but should generally be considered with the Nubian and Great Artesian aquifers as non-renewable. Of the renewable aquifers, all except the Guarani see depletion in excess of recharge, meaning their water tables are falling over time. We also compute the ratio of groundwater use to stock which shows differences in intensity of use to stock. We do not have estimates of discharge in each of these basins which would help complete a picture of the groundwater balance in each system.

Basins which are drier and more heavily depleted have high use to recharge ratios. A high use-to-recharge ratio suggests some local areas are suffering large declines in stock, which lead to various externalities. It is noticeable that in basins with significant land subsidence that the ratio is relatively high, like the Central Valley Aquifer. If we also consider the saturated thickness and remaining stock, a high ratio may also suggest loss of some ability to pump in local areas. The loss of access to groundwater could be seasonal, like in the Ganges basin, or permanent as in some areas in the High Plains. When near the coast, a high use to recharge ratio increases the risk of seawater intrusion, as in the Arabian aquifers.

The value of governance is largely derived from the value of groundwater, the cost of the externalities, and the costs of governance. Externalities can also impose salient damage to groundwater users, which can spur stakeholders to recognize the large benefits of collective action. Externalities such as seawater intrusion which can destroy the value of groundwater for drinking and irrigation can spur collective action to reduce pumping near the coast. Local externalities, such as the risk of exhaustion, can drive different tiers of governance action within basins. An example of this is in the High Plains aquifer where collective action varies across local conditions which have spurred some areas to pursue water right retirement or uniform pumping restrictions.

Despite the depletion of many aquifers over time, large amounts of underground storage limit the risk of running out of groundwater. Instead, local externalities described in the seventh column of table 3 drive the level of governance characterized in the eighth column. For instance, groundwater markets over the High Plains Aquifer were developed after the reduction of stream flows. Management efforts to close boreholes in Australia occurred in response to losses in artesian pressure. Groundwater markets and limitations on extraction over the Calama Aquifer have been developed after groundwater pumping reduced water flows to surface rights holders.

In India, pumping is generally unrestricted and agricultural water demand is high. Wells over shallow aquifers are seasonally dry, while deeper wells provide more water in the short term but see decreases in stored water capacity year over year (Fishman et al 2011). Where longer-term depletion is reducing groundwater levels, small-scale heterogeneity in subsurface rock leads some wells to go dry. On these lands, the amount of agricultural production decreases by 45-50% relative to nearby farms with wells that retain water, leading to decreases in on-farm income (Blakeslee 2020). India already faces a difficult governance challenge due to relatively weak underlying institutions and high transactions costs as a result of high numbers of users. The additional heterogeneity, at the local level, as well as geographically broader differences in management options for shallow and deep aquifers, suggests another barrier to widespread coordinated governance action.

In Australia, a reduction piezometric pressure has garnered efforts aimed at restoring pressure to the aquifer and maintaining discharge at artesian wells, especially in the arid regions dependent on these discharges. Each state in the federation is responsible for their own water management. In 1996, the Groundwater National Reforms required all boreholes to be licensed and in 2000, the Australian government adopted a strategic plan for the basin which has led to improved governance and restrictions water extraction from wells, set back requirements, and trading programs. Since water is discharged in many places throughout the basin, sometimes naturally, the focus has been to cap wasteful discharges and become more efficient in water usage (Habermehl, 2006).

Governance to address emerging externalities may entail a transition between governance tiers. On the High Plains aquifer in Kansas, the advent of center pivot irrigation and more easily accessible energy after World War II led to large amounts of well drilling for crop irrigation in the 1950s and 1960s, resulting in local areas of rapid depletion. Although the state required wells to receive permits before they were drilled, this requirement proved ineffective at preventing “wild west” like drilling of wells. In the 1960s groundwater users petitioned the state for local control, forming five groundwater management districts that initially implemented well spacing and area closures, but which have over time implemented local areas of uniform cutbacks to address surface water depletion and local areas of sustained drawdown (Edwards 2016). The transition between tiers in Kansas illustrates the importance of nested governance and effective recognition of higher levels of authority of local resource control (Ostrom 1990).

Transaction costs can also limit transitions between governance tiers. The Central Valley Aquifer is designated as being in critical overdraft by California and users would likely benefit from the implementation of additional management controls to address large areas of surface subsidence and drying streams. But the aquifer is large with many users including powerful agricultural and urban interests that disagree on the correct management approach (Ayres et al. 2018). As a result, the basin has seen fragmented governance and limited effectiveness at broadly implementing more stringent pumping controls. In some subareas of the basin, however, users have found common cause to import water and recharge their portion of the aquifer, suggesting management approaches that economize on transaction costs are potentially viable alternatives when broad management actions are infeasible (Williamson 1981).

Table 3. Economic Factors and Observed Governance of Select Aquifers

Basin	Recharge (net km^3/yr)	Use (km^3/yr)	Stock (km^3)	Recharge Ratio	Stock Ratio	Externalities	Governance
Ogallala[1,3]	6-8	~17	15,000	2.43	0.12%	LD, SF, BR	II-V
Central Valley, CA[1,3]	7	~11	1,130	1.57	0.97%	SF, LD	II-III
North China Plain[1,3,8]	49.2	*	6,000	*	*	LD, SU, SI	II
Northern India[1,2,8]	176	230	31,000	1.31	0.74%	LD, BR, RI	I-II
Guarani[5,6]	45-55	1.0	30,000	.02	0.003%	NA	I
Mancha Aquifers[7]	0.6	1.01	10.5	1.68	9.6%	SF,AP	II-III
Calama[4]	0.2	0.3	**	1.5	**	SF	V
Arabian[1-3]	1-2.76	16	2,185	5.8	0.62%	LD,SI	II
Nubian[1,2]	-0.2	2.2	14,470	NR	0.015%	RI,SF	I-II
Great Artesian[2,9]	~1	0.55	8,700	NR	0.0063%	AP	I-III

Notes: Table provides referenced estimates for recharge, use and stock that may be highly uncertain and contain significant rounding areas. The Use:Recharge and Use:Stock ratios are calculated by the authors based on the numbers in the table. Recharge numbers are not always clearly characterized as net of depletion, and estimates in this table may or may not subtract out depletion. Externality and governance data are based on author assessments of existing literature on each aquifer and externalities are selected to represent primary externalities of concern, although other externalities may be present. *Authors were unable to find a clear estimate of use for the North China Aquifer. **An estimate of the stock of water in the Calama Aquifer was not available. Externalities: SF-depletion of surface flows; LD-local areas of rapid drawdown, BR-bedrock interactions; SU-subsidence; RI-loss of buffer to mitigate risk; SI-seawater intrusion; AP-loss of artesian pressure; NA-not currently problematic.

Sources: [1]Konikow 2011; [2]Foster and Loucks (2006); [3]Margat and Van der Gun, 2013; [4]Calama Basin numbers are highly uncertain and come from government reports DGA (2003) and DGA (2005) as reported by Edwards et al (2018) and Jordan et al. (2015); [5]Sindico et al (2018); [6]Foster et al (2009).; [7]Apperl (2015) and Esteban and Albiac (2011).; [8] Richey et al. (2015).;[9] Herczeg (2008).

Even basins in tiers IV and V face ongoing challenges, reiterating the point that governance is a process of balancing costs and benefits, and good governance does not necessarily require the progression from less stringent to more stringent management. In the Antofagasta region of Chile, which houses the Calama Aquifer, nearly all surface water is fed by the groundwater system, and extractions for mining occurred above the seeps and diversion points that feed wetlands and provide water to indigenous villages. The allocation of groundwater is determined by the country's 1981 water code, which established tradable water rights that were separable from the land. When fully enforced, this system establishes the limit of groundwater extraction in a basin at the level of recharge, allocates these rights to individuals, and allows full trading. However, the original water code included few environmental controls (Bauer, 1997). As a result, mining water extraction has reduced water tables and surface flows, leading to declines in arable land and wetlands. Recent policy changes have statutorily enforced restrictions on transfers that could further lower water tables and the basin is generally closed to new pumping rights (Hearne and Donoso 2014; Edwards et al 2018).

Additional evidence of the local nature of groundwater problems and solutions is found in the governance outcomes of strongly centralized governments. In China, recent changes to enact a permit system with the potential for water right transfers (Zheng et al. 2012) have been hindered by poorly defined rights and the poor performance of local institutions (Chen et al. 2018). In Saudi Arabia, where governance of groundwater is largely controlled by the state and landowners, state planning has been the cause of groundwater depletion. Heavy irrigation was largely induced in the 1980s through business sector and investment from the wealthy (Elhadj, 2004). Management is loosely defined across the aquifer and depletion is largely by design based on the governmental objectives of producing their own food.

6. Discussion

This qualitative work attempts to highlight how externalities and the value of groundwater can lead to different governance institutions. We provide a framework in which the benefits and costs of collective action guide the choice of groundwater governance options. Through a qualitative cross-basin comparison we find that areas with high values of groundwater and greater externalities often undertake governance actions associated with higher transaction costs. The tiers of groundwater governance in table 1 are chosen endogenously, with both the benefits and costs of collective action affecting observed governance.

There are potential shortcomings of comparing large groundwater basins across the world. Information is imperfect and many of the groundwater estimates are made with significant uncertainty. Data is collected with different methods based on the country of origin. By focusing on large units for analysis we may gloss over important local governance institutions within sub-basins. For instance, the Mancha aquifers described in this paper have surprisingly different governance outcomes, despite sharing many similarities (Estiban and Albiac 2011).

An interesting challenge in comparing groundwater governance institutions is that many rules and approaches can be used concurrently. For instance, the goal of groundwater governance is not to reach the highest tier in our framework, or to be solely self-governing; rather multi-levels of governance can be complementary when coordinated. Top-down and bottom-up approaches can be complements in governance. Threats of top down restrictions may result in more efficient bottom-up efforts to enact collective action. In contrast, top-down goals of extraction limitations may be challenged by local users in regions where the immediate benefits of irrigation are salient. Effectively managing long-term extraction is not the priority of a subsistence farmer with limited opportunities for earning income and growing food. Sometimes, and especially where groundwater stocks are large, sustainable governance could be a second-order concern. In northern China, heavily extracted aquifers have reduced poverty (Huang et al., 2006).

Another challenge in understanding governance is incorporating cultural differences and preferences into the analysis. Certain rules and the process to make those rules depend on local customs. When enacting governance at a local level there is a need to understand culture and the history of governance in the area. Social scientists armed with good economics knowledge are likely to need domain specific knowledge of cultures and customs for successful transmission of governance knowledge. Governance also faces added challenges when it spans multiple countries, for instance the Nubian and Guarani aquifers, due to the increased transaction costs to developing institutions. Differing language and cultures add complexity and information sharing becomes critical, and neighboring countries may differ in legal traditions and the current state of intra-country governance. However, because externalities are local, transboundary governance provides a framework for the shared resource only in the immediate vicinity of the border. It does not solve internal governance challenges near the border and a lack of transboundary governance should not be viewed as a barrier to governance away from the border. On the Guarani aquifer, the primary areas of concerns are the drawdown of groundwater levels around international borders and the lack of knowledge about the lateral flows between countries (Voss and Soliman, 2014).

Empirical groundwater economics is dependent on data and modeling of the externalities to understand the potential gains from management. Sometimes models of groundwater extraction contain detailed groundwater dynamics but limited aspects of water demand or institutions. Models may have specific domains in which they are useful, and the researcher must carefully select models when attempting to inform policy. Many sub-basins suffer from multiple externalities and joint problems relating to water quality and water quantity. It is often easiest to focus on one externality at a time, which is often how research gets done. A key challenge is understanding when externalities and governance should be considered multi-dimensional. Agent-based and computational modeling holds promise to help understand the dynamics of complex systems with multi-dimensional issues (Gailliard et al. 2015).

More data-intensive approaches should incorporate detailed micro-level datasets into the public domain to compare local governance efforts. This relies on states or nations to collect the relevant data. AquaSTAT, from the FAO, is an example of a national level data repository. However, there needs to be more repositories that house micro-level basin information. Common datasets with both physical, historical, and economic data is needed to establish micro-level evidence for the success of different institutions under different conditions. In particular, detailed data on well numbers and locations, as well as rates of pumping, are typically not available and such data may not even be collected in many cases.

Another fruitful area of research is to incorporate more behavioral economics into groundwater governance research. Aspects such as framing (Menegaki et al. 2009), cognitive processes (Broznya et al. 2018), forecasting (Tong and Feiler 2017), learning (Rodela 2012), and salience to risk (McCoy and Zhao 2018) are all areas in economics that can be incorporated into groundwater research to a greater extent. The benefits to such approaches are to find more effective strategies to describe behavior and design policies which meet the increasing challenges to groundwater governance.

7. Conclusion

This article provides an economic framework for understanding and evaluating groundwater governance across the globe. Aquifer drawdown, extraction in excess of recharge, occurs in most of the basins we analyze. Economic analysis suggests this drawdown is likely too rapid because of the common pool problem: pumpers fail to internalize all the social costs of their individual pumping. However, governance is not required to prevent these aquifers from running out of water in the near-term because most aquifers have large reserves. Instead, governance addresses the externalities associated with decreasing water table elevations, and in most cases these problems are defined by local conditions—both human behavior and hydrogeological properties. Emerging hydrologic models, geospatial and remote-sensed data, and micro-level pumping and economic data offer powerful tools for identifying and addressing externalities. However, the analysis of groundwater management approaches must also incorporate the transaction costs of coordination and implementation. Governance cannot be evaluated strictly based on what type of management program has been implemented, i.e. a tier-V regime is not necessarily better than a tier-III regime. Instead, effective governance balances management approaches that reduce common pool losses with the transaction costs of creating and running the regime. Analysis of governance effectiveness requires local hydrological, institutional, and social context.

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