2020

The Economics of Groundwater Governance Institutions Around the Globe

Eric C. Edwards

Todd Guilfoos

This is a pre-publication author manuscript of the final, published article.

A. TITLE PAGE

i. The Economics of Groundwater Governance Institutions Across the Globe

ii. Eric C. Edwards, *Department of Agricultural and Resource Economics; North Carolina State University; eric.edwards@ncsu.edu*

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

iii. Date of original submission: May 9, 2020

Date of acceptance: August 27, 2020

iv. JEL Codes: Q25, Q28,

v. Keywords: Groundwater, Governance, Externalities, Irrigation, Institutions

vi. Editor in charge of manuscript: Daniel Petrolia

vii. Acknowledgements and/or disclaimers: The authors would like to thank participants at the American Geophysical Union Fall Meeting, and attendees at the Seminar in Water Economics Online (SWELL) for feedback on earlier versions of this paper. We also thank Terry Jordan, Manuel Pulido Velázquez, and Jose Albiac for sharing information on physical and governance characteristics of specific aquifers and David Sutherland for help in creating figures. This work was supported by the USDA National Institute of Food and Agriculture, Hatch project 1017720 and multistate project 1020662.

B. ABSTRACT

This article provides an economic framework for understanding the emergence and purpose of groundwater governance across the globe. We examine 10 basins located on six continents via an integrated assessment along three dimensions: characteristics of the groundwater resource; externality problems; and governance institutions. Groundwater governance addresses local externalities to balance the benefits of reducing common pool losses with the costs of doing so. While broad, basin-wide solutions to open access pumping are limited, spatially localized externality problems raise the benefits of management actions, allowing for the implementation of more stringent pumping controls in certain areas.

C. MAIN TEXT

1. Introduction:

Groundwater aquifers supply drinking water to approximately 50% of the world's population (Connor, 2015) 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 and agricultural 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 (Aeschbach and Gleeson, 2012). The world's aquifers remain largely open-access resources, with overlying landowners free to pump water subject to few restrictions (Konikow and Kendy, 2005). 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 (Mukherji and Shah, 2005). Contrasting the lack of compelling studies of groundwater governance factors, increased groundwater pumping monitoring, 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 generally about groundwater physical processes and interactions with human behavior, but how to translate this knowledge into specific, micro-level models of human behavioral responses is less clear (Gorelick and Zheng, 2015).

For this paper, we define *governance* to be institutions that guide behavior and *management* as decisive action by an organization to reduce water extraction externalities. We utilize an economic framework to explain the emergence, purpose, and challenges of groundwater governance across the globe. Why does groundwater governance that fully internalizes externalities 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 incomplete. This is the focus of our work.

Groundwater users often disagree on the extent of the problem and the necessary solutions (Ayers et al., 2018); users face considerable challenges in monitoring the unobserved resource and linking cause and effect (Bredehoeft, 2011); and weak institutions limit the effectiveness of many plans to reduce drawdown (Schlager, 2007; p.143). 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 that these costs limit the completeness of the solution that is ultimately implemented (Demsetz, 1967; Libecap, 1989).

2. Background

Groundwater users share a resource where each pumper can reduce the water available to neighboring wells, decreasing future availability and increasing pumping costs. Under open access, pumpers do not consider the full opportunity cost of applying it to a different purpose or at a different time (Provencher and Burt, 1994). 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). Overlapping pumping effects can reduce or eliminate the flow of water to pumps (Peterson and Saak, 2018; Merrill and Guilfoos, 2017).

Economic-hydrologic models help predict where institutional controls on extraction may be beneficial. The early groundwater economics models suggested pumping externalities were limited, governance provided limited benefits, and given the expense, was unlikely to be undertaken (Gisser and Sanchez, 1980; Burness and Brill, 2001).[1] However, altering the initial assumptions increased modeled gains from management, for instance changing marginal pumping costs (Gisser and Sanchez, 1980; Guilfoos et al., 2013); allowing exhaustion of groundwater (Merrill and Guilfoos, 2017); adding well capacity constraints (Manning and Suter, 2016; Foster et al., 2015; Foster et al., 2017); or the addition of ecologically valuable outflows (Esteban and Albiac, 2011).

Additional insight has been obtained by incorporating lateral subsurface groundwater flows using Darcy's Law and the Theis Equation into economic models (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

---

[1] The model's results rely on the assumption of a bathtub-like basin, accessed by many pumpers, and where pumping at one location is instantaneously transmitted to others

groundwater economics, which incorporates heterogeneity in aquifers from well placement, crop choices, and physical properties such as recharge, saturated thickness, or hydraulic conductivity.

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).

The primary issue in groundwater depletion is human behavior, not geophysical processes. Groundwater provides two challenging issues to incentivize cooperative behavior in conserving water. First, the impacts of pumping and external costs 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 be myopic (Ostrom et al., 1992; Walker and Gardner, 1992; Ostrom et al., 1994). While is also possible that groundwater pumpers behave strategically (Pfeiffer and Lin, 2012; Liu et al., 2014; Oehninger and Lawell, 2020), more evidence is needed to establish the extent of spatially strategic behavior. 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 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 aquifers important to irrigated agricultural production. Section 3 provides an integrative framework for comparing the basins. Section 4 describes the basins in detail and section 5 draws general conclusions based on our economic framework. In section 6 we 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.

3. Integrative framework

In this section we develop a framework for systematically evaluating groundwater governance. Figure 2 shows a two-cell groundwater model that can incorporate the basic dynamics found in economic-hydrologic models. The left panel depicts the physical setting, which is symbolically represented in the right panel. The figure can be imagined to expand to more cells to create a connected grid, all with different users. 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. The net benefit function for user *i* across the projected life of the aquifer (*T*) is:

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

Net benefits are an increasing function of groundwater pumped, w, and the elevation of the groundwater, h. We initially assume that groundwater has low salinity and groundwater use does not change the water quality of the remaining stock directly. 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 lift and thus lowers cost. Since groundwater extracted from the aquifer by all users affects the future state of the groundwater resource, we describe the change in elevation in the state equation:

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

Recharge, *r*, groundwater extracted, *w*, and transfers of water between parcels determine the change in elevation on a given parcel. The flow of groundwater is determined by the elevation differential of groundwater levels at neighboring parcels, $h_i - h_{-i}$, where the notation *-i* indicates all surrounding parcels. 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.

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 and the annual influx of recharge, r. More precipitation is generally linked to greater recharge, but the ratio of precipitation to recharge varies by basin and season (Jasechko et al., 2014). Basins that accumulate negligible amounts of natural recharge are considered non-renewable 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. Within basins, recharge can occur in one area and then flow to another. Different portions of an aquifer can be considered renewable and 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 determines the coefficient θ. Conductivity depends on soil/rock type. The major types of aquifers are 1) sand and gravel 2) sandstone 3) karst 4) volcanic and 5) basement (Margat and Van der Gun, 2013). The large groundwater systems we investigate here often include multiple types of sediment. Sand and gravel aquifer systems characterize the most commonly exploited systems and have high porosity and permeability, which lead to greater flow velocities for groundwater (Margat and Van der Gun, 2013).

Groundwater elevation

The elevation of groundwater is determined dynamically by the existing stock of water, current recharge into and flows out of the aquifer, and anthropogenic extractions. Groundwater systems are either confined or unconfined. Confined aquifers have impermeable layers that keep the aquifer pressurized. 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 affect water supply downstream. Heavy extraction of groundwater may reduce baseflow in streams when ground and surface water are connected (Mukherjee et al., 2018). Groundwater elevation is seasonal in many aquifers. In basins which are connected to river systems, surface water flows during dry seasons reduce groundwater elevation. The seasonal pumping of water itself also creates cones of depressions around high producing wells that can interfere with neighboring wells, with the drop in the water table limiting or eliminating production at neighboring wells during irrigation season.

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 (water for drinking and sanitation). In many of the aquifers explored in this paper, depletion occurs most severely due to irrigation demand. However, depletion is a state of the physical system determined by the properties of the groundwater system as well as water use decisions, and is not equivalent to water demand. Changes in the efficiency of water use, for instance improving irrigation practices, can change water demand functions without necessarily reducing physical depletion (Grafton et al., 2018).

B. Externalities

We modify the model in equation (1) 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, and are captured in the original specification in equation (1). The reduction in water table elevation also has the potential to cause additional externalities, of which we focus on six: loss of *artesian pressure*; depletion of *surface flows*; land *subsidence*; local areas of *rapid drawdown*; *bedrock interactions*; *seawater intrusion*.[2] Externalities are ordered arbitrarily since the importance of the externalities is local in nature and differs by circumstance. Figure 3 provides a detailed explanation of these six externalities.

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). 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). Groundwater basins can be conducive to collective management, hoever, 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 (Ostrom, 1990, p.90).

---

[2] Other externalities, water quality issues and pollution from overland activities, are excluded primarily for brevity and simplicity.

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:

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

In aggregate, the benefits of the policy are positive when:

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

As external costs increase, so do the aggregate benefits of conservation pumping regime. Conservation policies where the inequality in equation (5) is satisfied do not necessarily satisfy the inequalities in (4) for all users, or 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.

Formal modeling of this process is difficult because of the level of specificity required to understand policy alternatives and their translation to individual perceptions of benefits and costs. To model this complexity would require examining transaction costs as a function of specific cultural, legal, and political factors, for instance setting the total transaction costs as something like $\sum_i \kappa_i(\boldsymbol{Z})$, where κ_i maps a set of specific governance factors, $\mathbf{Z}$**,** into a numeric cost for each user.[3] Empirically, the factors underlying total transaction costs are largely unobservable or difficult to quantify at the aquifer scale. We abstract away from these complexities by asserting that governance involves comparing management strategies on both benefits and transaction costs.

The spatial nature of groundwater externalities determines local benefits and costs and is crucial in understanding the observed institutional response. Spatial externalities mean problems are typically

---

[3] 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.

localized; local solutions reduce the number (and often heterogeneity) of users who need to coordinate on a solution. However, spatial externalities can increase transaction costs where they create heterogeneous effects.[4] Spatial effects can also create complexities that hinder effective management.[5]

Drawing on the tradition of transaction cost economics, we systematically link the "principal dimensions" of groundwater challenges to the "principal attributes" of management solutions and then demonstrate how the "predicted alignments are corroborated by data" (Williamson, 2000, p.599). We develop a typology, shown in table 1, which categorizes management measures on their ability to control drawdown. Because the externality cost is increasing in drawdown, grouping management approaches provides an ordering across externality types. The proposed typology is intended to classify management control and graduated property rights over pumping decisions, but not the associated costs of doing so, and thus does not provide a ranking of net governance effectiveness. The tiers are typically increasing in transaction costs due to the greater controls and infrastructure needed to quantify and track water use and rights at higher tiers.

The first grouping, Tier I, combines a variety of limited management regimes that resemble open access conditions. Overlying landowners are allowed to pump, generally without binding limits. Tier II includes measures that require documentation and permitting of pumping, but generally do not affect existing users or provide a binding cap on individual extractions. 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 spacing restrictions may be placed on well permits.

Tier III approaches are characterized by limiting the ability of new entrants to drill wells, as well as 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 IV includes more significant individual regulation of pumpers, including binding caps on pumping and rule enforcement.

---

[4] 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).

[5] 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).

Measures in this tier provide regulatory authority to reduce pumping but do not provide positive individual incentives to conserve water or replenish the aquifer. The Tier V grouping includes the most complete tracking of water via assigned and tradable property rights, allowing groundwater markets and banking.

Because our modeled externalities are all caused by groundwater drawdown, solutions will typically involve limiting pumping. However, areas of rapid drawdown and bedrock interaction are also tied to well proximity and may be more easily resolved via well-spacing rules and areas closures. Externalities with a less localized spatial component, like land subsidence and loss of artesian pressure, might respond more readily to monitoring and uniform cutbacks. Externality type can also impact transaction costs, with issues related to seawater intrusion and reductions in surface flows often requiring heterogeneous action among a subgroup of users, which can increase transaction costs. We return to the question of governance tiers and externality types in the empirical discussion in section 5.

4. Background on Study Basins

We apply our integrated framework to groundwater governance issues in ten basins which we describe in more detail below. 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 groundwater footprint. The groundwater footprint is "the area required to sustain groundwater use and groundwater-dependent ecosystem services," with measures greater than one characterized as unsustainably exploited (Gleeson et al., 2012).

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 institutions hinder success (Birkenholtz, 2009). Bangladesh, like India, suffers from subsidies and cheap extraction costs, as well as 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, disrupting irrigation.

North China Plain Aquifer

The North China Plain Aquifer is located in a major floodplain and is extracted heavily for irrigation water. The deep parts of the aquifer are confined and essentially receive no recharge, creating concerns about groundwater mining. 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 has led to concerns over 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 world's copper supply (Edwards et al., 2018; Cochilco, 2014). 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.

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 an arid climate, it is non-renewable and has experienced heavy depletion due to large-scale production of wheat in Saudi Arabia from the 1980s to the late 2000s. This has led to a large loss in groundwater reserves (Elhadj, 2004), although there has been a shift in water policies in recent years (Ouda, 2014). The loss of groundwater reserves is the primary externality, though pumping costs (Müller et al., 2017), water quality (Rehman and Cheema, 2016), and sea water intrusion also are important externalities.

Nubian Aquifer System

The Nubian Aquifer System (NAS) is a sandstone aquifer in the Northeast of Africa underlying the Sudan, Egypt, and Libya. It is the largest fossil water aquifer in the world and is primarily used 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, due to the low amount of recharge, concerns about future groundwater availability for irrigation and drinking water. Oases and sabkhas can be dried up by the extraction, as natural outflows from the aquifer dwindle.

Great Artesian Aquifer

The Great Artesian Basin, the largest artesian basin in the world, has faced increasing problems as bore wells were drilled to access the pressurized water within sandstone deposits. The growth of borehole wells has resulted in the diminishing of natural discharge with some natural springs drying up entirely (Habermehl, 2006). 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 on water extraction from wells, set back requirements, and trading programs. It is noteworthy, however, that licensed wells are not necessarily monitored wells, and many issues with measuring and limiting the use of groundwater persist (Wheeler et al., 2020).

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 Brozović, 2013); and uniform pumping reductions to address long-run overdraft (Drysdale and Hendricks, 2018). 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 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 surface water flowing into the basin. 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. 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. 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 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 Synthesis

Table 3 provides an economic comparison of the 10 aquifer systems in our study. For each aquifer we compute the ratio of extraction to recharge as a measure of the extent to which use is sustainable. The Arabian Aquifer has minor amounts of recharge, but is generally classified as non-renewable. Of the renewable aquifers, all except the Guarani see depletion in excess of recharge, meaning their water tables have been drawn down over time. We do not have estimates of discharge in each of these basins, which prevents the calculation of a complete water balance. However, we do compute a rough use-to-stock ratio to provide information on the duration of time for which water reserves would be available, at current levels of extraction.

Generally, it is the renewable systems with large use-to-recharge ratios that see the highest tiers of governance, pointing to the governance level increasing in potential benefits of solving externality problems. India is a key exception. India faces a difficult governance challenge due to relatively weak underlying institutions and high transactions costs as a result of high numbers of users. In addition, heterogeneity at the local level as well as geographically broader differences in management options for shallow and deep aquifers suggest key transaction costs limiting coordinated governance action (Fishman et al., 2011; Blakeslee, 2020).

Each aquifer in the table, apart from the Mancha Aquifers, has a use-to-stock ratio under 1%. This implies that on average, at current pumping rates, full depletion would take more than 100 years. Management is generally not designed to prevent water from “running out.” Instead, local externalities described in the seventh column of table 3 drive the level of governance characterized in the eighth column. Surface water externalities appear the most likely to be noticed and addressed. The highest tiers of governance correspond to areas where groundwater pumping has disrupted surface flows: the Ogallala, Mancha, and Calama aquifers. Well-defined surface water property rights often legally require groundwater pumpers to take some action to reduce aquifer depletion. Conversely, the Central Valley aquifer, which also has a high recharge ratio, has seen limited governance of its key externalities related to drawdown and subsidence. Like the North China Plain and areas of the Ogallala, local drawdown externalities have been addressed using Tier II-III management approaches. And, despite the potentially high cost of land subsidence, basins facing this issue have not adopted high-tier levels of governance as a result of a misalignment of benefits and costs. In contrast to the depletion of surface flows, land subsidence does not generally lead to a firm legal claim against extractors, and thus pumpers, even as a group, do not bear the full costs of land subsidence.

Non-renewable systems also appear to have lower tiers of governance, which can be attributed to their limited interaction with surface water. The Great Artesian Aquifer has relatively more stringent management, and it is notable that despite being non-renewable, water is naturally discharged to the surface throughout the basin. The focus of management has been on water use efficiency and capping unused boreholes to limit the loss of natural springs (Habermehl, 2006).

Transaction costs can limit the transition to higher tiers of management, and these costs appear to differ with the type of externality. When surface water is depleted by groundwater pumping, surface property right holders have legal recourse, lowering uncertainty and transaction costs. Where transaction costs are high, users have utilized management approaches that economize on transaction costs when broad management actions are infeasible (Williamson, 1981). For example, agreements to cap pumping are often prohibitively expensive, but the importation of water to supplement pumping or recharge the aquifer is viewed favorably by pumpers. Examples include groundwater recharge in the Central Valley, importation of water to the North China Plain, and the desalination and pumping of water in Calama.

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. For instance, it does not appear the Guarani Aquifer needs tradeable permits and monitoring to address externalities. In addition, arriving at a high tier does not resolve many management issues or necessarily indicate effective governance. On the Calama Aquifer, Chile’s 1981 water code, which established tradable water rights that were separable from the land, is supposed to limit extraction to the level of recharge, allocate extraction rights to individuals, and facilitate full water 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).

Based on the intra-country heterogeneity in groundwater management approaches, we conclude that externalities and transaction costs, rather than national or regional government type or national or multinational water policy, are the key determinant of groundwater governance choices. Within Spain, the US, Australia, and Chile the success of groundwater governance varies across and even within groundwater basins. Centralized, authoritarian governments do not appear to have had success in limiting groundwater externalities. 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, state planning has been the cause of, rather than the solution to, groundwater depletion.

While local, nested institutions recognized by higher levels of authority can be effective (Ostrom, 1990), these institutions are weakened or not present under authoritarian regimes. In contrast, the High Plains Aquifer in the United States also saw ineffective governance and open-access drilling in the 1960s, but groundwater users in Kansas 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; Drysdale and Hendricks, 2018). While emerging research from China suggests there is potential for locally initiated water organizations (Chai and Zeng, 2018) the issue of decentralized control under authoritarian regimes remains a key hurdle (Yu et al., 2016).

6. Discussion

In this paper we provide a framework in which the benefits and costs of collective action guide the choice of groundwater governance options. The tiers of groundwater governance are chosen endogenously, with both the benefits and costs of collective action affecting observed governance. The goal of governance is to address externalities or reach specific policy goals of resource users. Moving up the tiers may or may not be beneficial. In fact, the lowest cost governance rules would be the best choice for the same net benefits. Moving up tiers typically only makes sense if the increased governance is able to generate larger gains in benefits.

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).

Another challenge in comparing groundwater governance institutions is that many rules and approaches can be used concurrently. The goal of groundwater governance is not to reach the highest tier in our framework, or to be solely self-governing; top-down and bottom-up approaches can be complements. 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).

Cultural differences and preferences also require consideration in performing comparative analysis. Rules, and the process under which those rules are made, depend on local customs. Social scientists armed with economic recommendations 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. 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.

Empirical groundwater economics is dependent on data and modeling of the externalities to understand the potential gains from management. Models of groundwater extraction may contain detailed groundwater dynamics, but be limited in describing aspects of water demand or institutions. These 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 modeling on one externality at a time; 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., 2014).

More data-intensive approaches should incorporate detailed micro-level datasets into the public domain to compare local governance efforts. This requires that governments collect the relevant data. However, detailed data on well numbers and locations, as well as rates of pumping, are typically not available. AquaSTAT, from the FAO, is an example of a national level data repository. However, more repositories that house micro-level basin information are needed. Common datasets with both physical, historical, and economic data can establish micro-level evidence for the success of different institutions under different conditions. Satellite data offers an especially promising data source for future research, as it offers the potential for consistent measurement of groundwater depletion across countries.

Another fruitful area of research is the incorporation of 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 of behavioral economics that can be incorporated into groundwater research to a greater extent. Such an approach could lead to more effective strategies to describe behavior and design policies to meet the increasing challenges to groundwater governance.

7. Conclusion

This article provides an economic framework for understanding and evaluating groundwater governance across the globe. Economic analysis suggests aquifer drawdown is likely too rapid in many areas because of the common pool problem: pumpers fail to internalize all the social costs of their individual pumping. Governance addresses the externalities associated with decreasing water table elevations, and in most cases these problems are defined by local conditions, i.e. both human behavior and hydrogeological properties. Our analysis of governance tiers across 10 major groundwater basins shows that the value of groundwater and type of externality tend to determine the level and type of groundwater governance in a basin. Aquifer drawdown, extraction in excess of recharge, occurs in most of the basins we analyze and aquifers with larger use-to-recharge ratios tend to have higher tiers of governance. However, externalities related to surface water depletion appear to be addressed in the study basins more often, and more completely, than other externalities.

Transaction costs can limit the transition to higher tiers of management, and many of these costs decrease as more information about the physical aquifer system becomes available. Emerging hydrologic models, geospatial and remote-sensed data, and micro-level pumping and economic data offer potential tools for identifying externalities and reducing transaction costs. Critically, the analysis of groundwater management approaches must incorporate the transaction costs of coordination and implementation. Governance cannot be evaluated strictly based on what type of management program has been implemented. A tier-V regime is not necessarily better than a tier-III regime because there are costs of implementation. 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.

D. REFERENCES

Aeschbach-Hertig, W. and Gleeson, T., 2012. Regional strategies for the accelerating global problem of groundwater depletion. Nature Geoscience, 5(12), p.853.

Allen, D.W., 2011. The institutional revolution: Measurement and the economic emergence of the modern world. University of Chicago Press. Alley, W.M., Healy, R.W., LaBaugh, J.W. and Reilly, T.E., 2002. Flow and storage in groundwater systems. science, 296(5575), pp.1985-1990.

Apperl, B., Pulido-Velazquez, M., Andreu Álvarez, J. and Karjalainen, T.K., 2015. Contribution of the multi-attribute value theory to conflict resolution in groundwater management application to the Mancha Oriental groundwater system, Spain. Hydrology and Earth System Sciences, 19(3), pp.1325-1337.

Ayres, A.B., Edwards, E.C. and Libecap, G.D., 2018. How transaction costs obstruct collective action: The case of California's groundwater. Journal of Environmental Economics and Management, 91, pp.46-65.

Ayres, A.B., Meng, K.C. and Plantinga, A.J., 2019. Do Property Rights Alleviate the Problem of the Commons? Evidence from California Groundwater Rights (No. w26268). National Bureau of Economic Research.

Babbitt, C., Gibson, K., Sellers, S., Brozović, N., Saracino, A., Hayden, A., Hall, M.D. and Zeller, S., 2018. The Future of Groundwater in California: Lessons in Sustainable Management from Across the West. Environmental Defenese Fund.

Barlow, P. and E. Reichard, 2010. Saltwater intrusion in coastal regions of North America. Hydrogeology Journal, 18: 247-60.

Bauer, C.J., 1997. Bringing water markets down to earth: The political economy of water rights in Chile, 1976–1995. World development, 25(5), pp.639-656.

Birkenholtz, T., 2009. Groundwater governmentality: hegemony and technologies of resistance in Rajasthan's (India) groundwater governance. Geographical journal, 175(3), 208-220.

Blakeslee, D., Fishman, R. and Srinivasan, V., 2020. Way Down in the Hole: Adaptation to Long-Term Water Loss in Rural India. American Economic Review, 110(1), pp.200-224.

Bredehoeft, J.D., Papadopulos, S.S. and Cooper, H.H., 1982. Groundwater: The water budget myth. Scientific basis of water resource management, 51, p.57.

Bredehoeft, J.D., 2011. Monitoring regional groundwater extraction: the problem. Groundwater, 49(6), pp.808-814.

Brozović, N., Sunding, D.L. and Zilberman, D., 2010. On the spatial nature of the groundwater pumping externality. Resource and Energy Economics, 32(2), pp.154-164.

Brozović Nicholas, and Richael Young, 2014. Design and Implementation of Markets for Groundwater Pumping Rights. In Water Markets for the 21st Century, 283–303. Dordrecht: Springer Netherlands.

Brozyna, C., Guilfoos, T., & Atlas, S., 2018. Slow and deliberate cooperation in the commons. Nature Sustainability, 1(4), 184-189.

Burness, H.S. and Brill, T.C., 2001. The role for policy in common pool groundwater use. Resource and energy economics, 23(1), pp.19-40.

Chai, Y. and Zeng, Y., 2018. Social capital, institutional change, and adaptive governance of the 50-year-old Wang hilltop pond irrigation system in Guangdong, China. International Journal of the Commons, 12(2).

Chen, J., Wu, H., Qian, H., & Li, X., 2018. Challenges and prospects of sustainable groundwater management in an agricultural plain along the Silk Road Economic Belt, north-west China. International journal of water resources development, 34(3), 354-368.

Closas, A., Molle, F. and Hernández-Mora, N., 2017. Sticks and carrots to manage groundwater over-abstraction in La Mancha, Spain. Agricultural Water Management, 194, pp.113-124.

Coase, R.H., 1960. The problem of social cost. In Classic papers in natural resource economics (pp. 87-137). Palgrave Macmillan, London.

Cochilco, 2014. Database of Statistics on Mineral Production. Available at http://www.cochilco.cl/estadisticas/produccion.asp.

Connor, R., 2015. The United Nations world water development report 2015: water for a sustainable world (Vol. 1). UNESCO publishing.

Demsetz, H., 1967. Toward a Theory of Property Rights. The American Economic Review, 57(2), pp.347-359.

DGA (Dirección General de Aguas), 2003. Evaluación de los Recursos Hídricos Sectores Calama y Llalqui, Cuenca del Río Loa: Dirección General de Aguas, Centro de Información de Recursos Hídricos Informe Técnico S.I.T. no. 85, http:// documentos .dga .cl /ADM3012 .pdf.

DGA (Dirección General de Aguas), 2005. Evaluación de Los Recursos Hídricos Superficiales en la Cuenca del Rio Loa. Santiago, Chile: Technical Report SDT No 192 (In Spanish).

Drysdale, K.W. and N.P. Hendricks, 2018. Adaptation to an Irrigation Water Restriction Imposed through Local Governance. Working Paper. URL: https://nphendricks.files.wordpress.com/2018/02/lema_did_2018-02-08.pdf

Edwards, Eric C., 2016. What lies beneath? Aquifer heterogeneity and the economics of groundwater management. Journal of the Association of Environmental and Resource Economists3(2), 453-491.

Edwards, E.C., Cristi, O., Edwards, G. and Libecap, G.D., 2018. An illiquid market in the desert: estimating the cost of water trade restrictions in northern Chile. Environment and Development Economics, 23(6), pp.615-634.

Elhadj, E., 2004. Camels don't fly, deserts don't bloom: An assessment of Saudi Arabia's experiment in desert agriculture. Ocasional paper, 48(6).

Esteban, E. and Albiac, J., 2011. Groundwater and ecosystems damages: Questioning the Gisser–Sánchez effect. *Ecological Economics*, *70*(11), pp.2062-2069.

Fishman, R., Siegfried, T., Raj, P., Modi, V., and Lall, U., 2011. Over-extraction from shallow bedrock versus deep alluvial aquifers: Reliability versus sustainability considerations for India's groundwater irrigation. Water Resources Research, 47(12):W00L05.

Foster, T., Brozović, N., & Butler, A. P., 2015. Analysis of the impacts of well yield and groundwater depth on irrigated agriculture. Journal of Hydrology, 523, 86-96.

Foster, T., Brozović, N., & Speir, C., 2017. The buffer value of groundwater when well yield is limited. Journal of Hydrology, 547, 638-649.

Foster, S. and Loucks, D.P., 2006. Non-renewable groundwater resources. Series on groundwater, (10).

Foster, S., Hirata, R., Vidal, A., Schmidt, G. and Garduño, H., 2009. The Guarani Aquifer initiative—towards realistic groundwater management in a transboundary context. World Bank.

Gailliard, N., Barreteau, O., & Richard-Ferroudji, A., 2014. Participatory policy making in practice: simulating boundary work in water governance. In Advances in social simulation (pp. 333-342). Springer, Berlin, Heidelberg.

Gisser, Micha, and David A. Sanchez, 1980. Competition versus optimal control in groundwater pumping. Water resources research 16(4), 638-642.

Gleeson, T., Wada, Y., Bierkens, M.F. and Van Beek, L.P., 2012. Water balance of global aquifers revealed by groundwater footprint. Nature, 488(7410), pp.197-200.

Gorelick, S.M. and Zheng, C., 2015. Global change and the groundwater management challenge. Water Resources Research, 51(5), pp.3031-3051.

Grafton, R.Q., Williams, J., Perry, C.J., Molle, F., Ringler, C., Steduto, P., Udall, B., Wheeler, S.A., Wang, Y., Garrick, D. and Allen, R.G., 2018. The paradox of irrigation efficiency. Science, 361(6404), pp.748-750.

Guilfoos, T., Khanna, N., & Peterson, J. M., 2016. Efficiency of viable groundwater management policies. Land Economics, 92(4), 618-640.

Guilfoos, T., Pape, A. D., Khanna, N., & Salvage, K., 2013. Groundwater management: The effect of water flows on welfare gains. Ecological Economics, 95, 31-40.

Habermehl, M. A., 2006. The great artesian basin, Australia. Into the well from which you drink do not throw stones, 82.

Halder, 2019. https://timesofindia.indiatimes.com/city/delhi/digging-deep-for-drinking-water-you-may-have-to-shell-out-rs-10000-as-fine/articleshow/70079981.cms

Harou, J.J. and Lund, J.R., 2008. Ending groundwater overdraft in hydrologic-economic systems. Hydrogeology Journal, 16(6), p.1039.

Hearne, R., & Donoso, G., 2014. Water markets in Chile: are they meeting needs?. In Water markets for the 21st century (pp. 103-126). Springer, Dordrecht.

Herczeg, A., 2008. Background report on the Great Artesian Basin. A report to the Australian Government from the CSIRO Murray- Darling Basin Sustainable Yields Project. CSIRO, Australia. 18pp.

Huang, Q., Rozelle, S., Lohmar, B., Huang, J., & Wang, J., 2006. Irrigation, agricultural performance and poverty reduction in China. *Food Policy*, *31*(1), 30-52.

Huang, Qiuqiong, Jinxia Wang, Scott Rozelle, Stephen Polasky, and Yang Liu, 2013. The effects of well management and the nature of the aquifer on groundwater resources. American Journal of Agricultural Economics 95 (1): 94–116.

Ifft, J., Bigelow, D.P. and Savage, J., 2018. The Impact of Irrigation Restrictions on Cropland Values in Nebraska. Journal of agricultural and resource economics, 43(1835-2018-2978), pp.195-214.

Jasechko, S., Birks, S.J., Gleeson, T., Wada, Y., Fawcett, P.J., Sharp, Z.D., McDonnell, J.J. and Welker, J.M., 2014. The pronounced seasonality of global groundwater recharge. Water Resources Research, 50(11), pp.8845-8867.

Jeanne, P., Farr, T. G., Rutqvist, J., & Vasco, D. W., 2019. Role of agricultural activity on land subsidence in the San Joaquin Valley, California. Journal of hydrology, 569, 462-469.

Jordan, T., Lameli, C.H., Kirk-Lawlor, N. and Godfrey, L., 2015. Architecture of the aquifers of the Calama Basin, Loa catchment basin, northern Chile. Geosphere, 11(5), pp.1438-1474.

Kanazawa, M.T., 1992. Econometric estimation of groundwater pumping costs: A simultaneous equations approach. Water resources research, 28(6), pp.1507-1516.

Kuwayama, Yusuke, and Nicholas Brozović, 2013. The regulation of a spatially heterogeneous externality: Tradable groundwater permits to protect streams." Journal of Environmental Economics and Management 66(2), 364-382.

Koundouri, Phoebe, Catarina Roseta-Palma, and Nikolaos Englezos, 2017. Out of sight, not out of mind: developments in economic models of groundwater management. International Review of Environmental and Resource Economics 11(1), 55-96.

Konikow, L. and E. Kendy, 2005. Groundwater depletion: A global problem. Hydrogeology Journal, 13: 317-20.

Konikow, L. F., 2011. Contribution of global groundwater depletion since 1900 to sea-level rise. *Geophysical Research Letters*, *38*(17).

Libecap, G.D., 1989. Distributional issues in contracting for property rights. Journal of Institutional and Theoretical Economics (JITE)/Zeitschrift für die gesamte Staatswissenschaft, pp.6-24.

Libecap, G.D., 1993. Contracting for property rights. Cambridge university press.

Lin Lawell, C-Y. Cynthia., 2016. The management of groundwater: Irrigation efficiency, policy, institutions, and externalities. Annual Review of Resource Economics 8, 247-259.

Liu, Z., Suter, J. F., Messer, K. D., Duke, J. M., & Michael, H. A., 2014. Strategic entry and externalities in groundwater resources: Evidence from the lab. Resource and energy economics, 38, 181-197.

Manjunatha, A.V., Speelman, S., Chandrakanth, M.G. and Van Huylenbroeck, G., 2011. Impact of groundwater markets in India on water use efficiency: A data envelopment analysis approach. Journal of environmental management, 92(11), pp.2924-2929.

Manning, D., & Suter, J., 2016. Well Capacity and the Gains from Coordination in a Spatially Explicit Aquifer. In Selected Paper Presented at AAEA 2016 Annual Meeting.

Margat, J., & Van der Gun, J., 2013. Groundwater around the world: a geographic synopsis. Crc Press.

McCoy, S. J., & Zhao, X., 2018. A city under water: A geospatial analysis of storm damage, changing risk perceptions, and investment in residential housing. Journal of the Association of Environmental and Resource Economists, 5(2), 301-330.

Menegaki, A. N., Mellon, R. C., Vrentzou, A., Koumakis, G., & Tsagarakis, K. P., 2009. What's in a name: Framing treated wastewater as recycled water increases willingness to use and willingness to pay. Journal of Economic Psychology, 30(3), 285-292.

Merrill, N. H., & Guilfoos, T., 2017. Optimal groundwater extraction under uncertainty and a spatial stock externality. American journal of agricultural economics, 100(1), 220-238.

Müller, M. F., Müller-Itten, M. C., & Gorelick, S. M., 2017. How Jordan and Saudi Arabia are avoiding a tragedy of the commons over shared groundwater. Water Resources Research, 53(7), 5451-5468.

Mukherjee, A., Bhanja, S.N. and Wada, Y., 2018. Groundwater depletion causing reduction of baseflow triggering Ganges river summer drying. Nature: Scientific Reports, 8(1), pp.1-9.

Mukherji, A. and Shah, T., 2005. Groundwater socio-ecology and governance: a review of institutions and policies in selected countries. Hydrogeology Journal, 13(1), pp.328-345.

Nachbaur, J.W., 2007. The economics of groundwater governance. University of California, Santa Barbara.

Oehninger, E. B., & Lawell, C. Y. C. L., 2019. Property rights and groundwater management in the High Plains Aquifer. Resource and Energy Economics, 101147.

Ostrom, E., 1990. Governing the commons: The evolution of institutions for collective action. Cambridge university press.

Ostrom, E., Walker, J., & Gardner, R., 1992. Covenants with and without a sword: Self-governance is possible. American political science Review, 86(2), 404-417.

Ostrom, E., Gardner, R., Walker, J., Walker, J. M., & Walker, J., 1994. Rules, games, and common-pool resources. University of Michigan Press.

Ostrom, E., 1999. Coping with tragedies of the commons. Annual review of political science, 2(1), pp.493-535.

Ouda, O. K., 2014. Impacts of agricultural policy on irrigation water demand: A case study of Saudi Arabia. International Journal of Water Resources Development, 30(2), 282-292.

Pfeiffer, L., & Lin, C. Y. C., 2012. Groundwater pumping and spatial externalities in agriculture. Journal of Environmental Economics and Management, 64(1), 16-30.

Peterson, J.M. and Saak, A.E., 2018. Spatial Externalities in Aquifers with Varying Thickness: Theory and Numerical Results for the Ogallala Aquifer. Journal of Natural Resources Policy Research, 8(1-2), pp.44-65.

Provencher, B. and Burt, O., 1994. A private property rights regime for the commons: The case for groundwater. American Journal of Agricultural Economics, 76(4), pp.875-888.

Qureshi, A. S., Ahmed, Z., & Krupnik, T. J., 2014. Groundwater management in Bangladesh: an analysis of problems and opportunities.

Rehman, F., & Cheema, T., 2016. Effects of sewage waste disposal on the groundwater quality and agricultural potential of a floodplain near Jeddah, Saudi Arabia. Arabian Journal of Geosciences, 9(4), 307.

Richey, A. S., Thomas, B. F., Lo, M. H., Famiglietti, J. S., Swenson, S., & Rodell, M.,2015. Uncertainty in global groundwater storage estimates in a Total Groundwater Stress framework. Water Resources Research, 51(7), 5198-5216.

Rodela, R., Cundill, G., & Wals, A. E., 2012. An analysis of the methodological underpinnings of social learning research in natural resource management. Ecological economics, 77, 16-26.

Saak, A. E., & Peterson, J. M., 2007. Groundwater use under incomplete information. Journal of Environmental Economics and Management, 54(2), 214-228.

Schlager, E., 2007. Community management of groundwater. The agricultural groundwater revolution: Opportunities and threats to development, 3, pp.131-152.

Siebert, S., Burke, J., Faures, J.M., Frenken, K., Hoogeveen, J., Döll, P. and Portmann, F.T., 2010. Groundwater use for irrigation—a global inventory. Hydrology and earth system sciences, 14(10), pp.1863-1880.

Sindico, F., Hirata, R. and Manganelli, A., 2018. The Guarani Aquifer System: From a Beacon of hope to a question mark in the governance of transboundary aquifers. Journal of Hydrology: Regional Studies, 20, pp.49-59.

Smith, S.M., Andersson, K., Cody, K.C., Cox, M., and D. Ficklin, 2017. Responding to a groundwater crisis: The effects of self-imposed economic incentives. Journal of the Association of Environmental and Resource Economists, 4(4), 985-1023.

Suter, J. F., Duke, J. M., Messer, K. D., & Michael, H. A., 2012. Behavior in a spatially explicit groundwater resource: Evidence from the lab. American Journal of Agricultural Economics, 94(5), 1094-1112.

Tong, J., & Feiler, D., 2017. A behavioral model of forecasting: Naive statistics on mental samples. Management Science, 63(11), 3609-3627.

Tsvetanov, T., & Earnhardt, D.,Forthcoming. The effectiveness of a water right retirement program at conserving water. Land Economics.

Villar, P. C. and W.C. Ribeiro, 2011. ‘The Agreement on the Guarani Aquifer: a new paradigm for transboundary groundwater management? Water International, 36(5): 646-660, 2011, available at: http://www.tandfonline.com/doi/full/10.1080/02508060.2011.603671.

Walker, J. M., & Gardner, R., 1992. Probabilistic destruction of common-pool resources: experimental evidence. The Economic Journal, 102(414), 1149-1161.

Wheeler, S.A., Carmody, E., Grafton, R.Q., Kingsford, R.T. and Zuo, A., 2020. The rebound effect on water extraction from subsidising irrigation infrastructure in Australia. Resources, Conservation and Recycling, 159, p.104755.

Wheeler, S.A., Schoengold, K. and Bjornlund, H., 2016. Lessons to be learned from groundwater trading in Australia and the United States. In Integrated Groundwater Management (pp. 493-517). Springer, Cham.

Williamson, O.E., 1981. The economics of organization: The transaction cost approach. American journal of sociology, 87(3), pp.548-577.

Williamson, O.E., 2000. The new institutional economics: taking stock, looking ahead. Journal of economic literature, 38(3), pp.595-613.

Yang, X. L., Chen, Y. Q., Steenhuis, T. S., Pacenka, S., Gao, W. S., Ma, L., ... & Sui, P., 2017. Mitigating groundwater depletion in North China Plain with cropping system that alternate deep and shallow rooted crops. Frontiers in plant science, 8, 980.

Yu, H.H., Edmunds, M., Lora-Wainwright, A. and Thomas, D., 2016. Governance of the irrigation commons under integrated water resources management–A comparative study in contemporary rural China. Environmental Science & Policy, 55, pp.65-74.

Zekri, S., 2008. Using Economic Incentives and Regulations to Reduce Seawater Intrusion in the Batinah Coastal Area of Oman. Agricultural Water Management, 95: 243-52.

Zheng, H., Wang, Z., Hu, S., & Wei, Y., 2012. A comparative study of the performance of public water rights allocation in China. Water resources management, 26(5), 1107-1123.

E. FIGURE LEGENDS

Figure 1. Groundwater basins used in this study 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.

Figure 2. Two-cell groundwater model with two users

Figure 3. Diagram of groundwater pumping externalities

Notes: The left panel shows the natural groundwater system without pumping. While most groundwater systems are likely to be in flux within a season and over time as conditions change, a static equilibrium is assumed for illustrative purposes. A confined aquifer provides subsurface pressure for a free-flowing artesian well, 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. Pumping near the coast (W_6) can break the natural barrier freshwater aquifers provide, leading to costly brackish water intrusions into coastal wells.

F. TABLES

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); Ifft et al. (2018)
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)

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).

Table 3. Economic Factors and Observed Governance of Select Aquifers

Basin	Recharge (net km^3/yr)	Use (km^3/yr)	Stock (km^3)	Use/Recharge Ratio	Use/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%	LD, SU	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: The table provides referenced estimates for recharge, use and stock that may be highly uncertain and contain significant rounding areas. The Use/Recharge Ratio (use divided by recharge) and Use/Stock Ratios (use divided by total stock) 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 Plain Aquifer. **An estimate of the stock of water in the Calama Aquifer is not currently 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).