

# THE EFFECTS OF WELL MANAGEMENT AND THE NATURE OF THE AQUIFER ON GROUNDWATER RESOURCES

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We compare groundwater use under collective well management in China, where village leaders allocate water among households, and under private well management where farmers either pump from their own wells or buy water from wells owned by other farmers. Villages are divided into connected or isolated groups depending on whether there are lateral groundwater flows between aquifers underlying a village and neighboring ones. In rural China, households under collective well management use less water. Even under collective management, households located in connected villages use more water, indicating that the connectedness of the aquifers may undermine leaders' incentives to conserve water.

*Key words:* community-based management, connected village, isolated village, collective well management, private well management.

*JEL codes:* O17, Q15, Q25.

The management of local common property resources (CPR) is among the most important issues in the study of rural area development and resource conservation in developing countries. Some scholars argue that local communities have the ability to manage local commons that avoids the tragedy of commons (Baland and Platteau 1996; Bromley 1992; Ostrom 1990; Wade 1988).<sup>1</sup> The underlying assumption is that since local communities possess time- and place-specific knowledge (e.g. Ostrom 1990), they would be better managers of natural resources than outside agents. Some also think that since communities have a long-term need for renewable resources near where they live, they have the incentive to manage their natural resources in a sustainable way.

Indeed, international funding agencies such as the World Bank have directed large sums of money and a great deal of effort toward community-based resource management programs. Some of the most significant actions have occurred in the water sector. More than 25 countries in Asia, Africa and Latin America have decentralized irrigation management and have transferred the control of resources to local communities (Vermillion 1997). Other scholars argue that rural communities have failed to develop controls to overcome the common pool incentives to overuse CPR, and their failures have resulted in resource degradation such as declines in soil fertility, extensive deforestation and overgrazing (e.g. Allen 1985; Perrings 1989).

Ultimately, whether communities can manage CPR to prevent the overexploitation of natural resources is an empirical question. There are successful examples: The Upper Republican Natural Resource District (URNRD) groundwater control program in the United States, one of the most comprehensive local efforts to manage the groundwater resource in the Ogallala region, had a significant impact in altering the rate of groundwater withdrawals (Stephenson 1996). There have also been failures: the empirical results from Lopez (1998) show that farmers in Côte d'Ivoire do not internalize even a small fraction of the external cost on biomass in their decisions to expand cultivated land

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<sup>1</sup> Along this line of research, most have focused on assessing the performance of village-level management and attempted to identify the general conditions that would lead to successful collective action in managing CPRs (Baland and Platteau 1996; Ostrom 1990; Wade 1988). A long list of factors has been identified, including the size of the group (Aggarwal 2000; Potete and Ostrom 2004) and wealth inequalities (Baland and Platteau 1998, 1999).

through deforestation or by shortening the length of the fallow periods. The explanation for the inefficient allocation of land under common property was the high costs of monitoring and other transaction cost involved in the design and implementation of institutional mechanisms to exploit the resource efficiently, particularly given the high population density. It could also be that most villages cannot afford to reduce the cultivated area since their livelihoods depend on it.

Despite the large number of studies, limited attention has been paid to the importance of the natural resource itself (Agrawal 2001). The lack of research on this topic is surprising because whether or not villages can manage resources in a sustainable way often depends crucially on the characteristics of the natural resource. For example, Naughton-Treves and Sanderson (1995) argue that the mobility and fugitive habits of wildlife make local management inadequate for effective biodiversity conservation. In another study, when examining a set of CPRs including fisheries, irrigation systems and groundwater basins, Schlager, Blomquist, and Tang (1994) find that users of the resources pursue different strategies and design different institutional arrangements to tackle CPR problems depending upon the characteristics of the resources.

Taking into account the nature of water resources is of particular importance when studying the management of groundwater resources. Brozović, Sunding, and Zilberman (2006) have shown that whether or not groundwater should be treated as a CPR depends on the nature of the aquifer. If an aquifer has low storativity and high transmissivity, groundwater can easily flow laterally across the aquifer.<sup>2</sup> As a result, the effect of any user's pumping is widely transmitted throughout the aquifer. In this case the aquifer is more appropriately modeled as a CPR. In contrast, an aquifer with high storativity and low transmissivity would be more akin to private property. Whether or not groundwater should be treated as a CPR or private property, of course, will have strong implications on how groundwater should be managed. Furthermore, Saak and Peterson (2007) show theoretically that the pumping

rate of a farmer depends on the speed of lateral flows between his well and the wells of his neighbors, which is modeled as a function of the transmissivity of the aquifer.

The present study has two goals, the first of which is to examine the effectiveness of community-based management of groundwater resources when accounting for the nature of the aquifer. This study is one of the few that empirically examines whether the physical characteristics of the natural resource is among the key determinants of the success of community-based management of CPRs. Both Brozović, Sunding, and Zilberman (2006) and Saak and Peterson (2007) have made significant contributions to the theoretical side of the economics of groundwater; their work, however, contains no empirical evidence.<sup>3</sup> Only a few studies (e.g. Shah 2009) have linked the nature of the aquifer to community-based groundwater management. Unlike most studies in the extensive literature on CPRs that are either based on just case studies ("small-N studies") or theoretical formulations (Poteete and Ostrom 2008), our study uses a set of survey data as well as econometric analysis to examine the questions of interest.

The second goal of the paper is to compare the effectiveness of different institutional arrangements at the community level on resource conservation. The study area of this paper is northern China. In rural China, "community" carries the same meaning as "village," the latter of which will be used in the rest of the paper. China's National Water Law, which was revised in 2002, stipulates that all property rights over groundwater resources belong to the national government, including the right to use, sell and/or charge for water. However, the effort to construct a regulatory framework has been weak. At the national level, there is no water regulation that specifically focuses on groundwater management issues (Wang et al. 2009). In rural areas, villages that lie above the aquifers have the de facto rights to the groundwater and manage

<sup>2</sup> Storativity is the amount of water released per unit area of aquifer in response to per unit decline in hydraulic head; transmissivity is a measure of how much water can be transmitted horizontally per unit of time in the aquifer (Freeze and Cherry 1979).

<sup>3</sup> Several other studies also look at the management of connected aquifers. Zeitouni and Dinar (1997) use a dynamic optimal control model to study the management of two aquifers that are adjacent and connected, one being a fresh water aquifer and the other being a saline water aquifer. Their focus is on water quality; they only use simulation analysis. Provencher and Burt (1994) study the optimal pumping policy for several connected aquifers in Madera County, California. Their focus is on the different methods of approximating the value function when numerically solving a dynamic programming problem. Again, neither study contains empirical evidence.

groundwater resources. Access to groundwater in an aquifer is restricted to villages that lie above it, and is often associated with the ownership of wells.<sup>4</sup> Furthermore, institutional arrangements within villages define the rules of groundwater governance and, in particular, water allocation rules. Specific institutional arrangements differ among rural villages. In some villages, wells are collectively owned and groundwater is managed by the village leader. In the literature, collective management is often defined as management by all the members in the village. In the case of rural China, when wells are collectively owned, in principle, groundwater is managed by all members of the village. In practice, however, the village leader (or a group of leaders that includes the party secretary and the village committee head), as the curator of local assets such as schools or roads, is in charge of managing groundwater. Households rarely participate in the decision-making process of water management. They manage their own plots but rely on the groundwater that is pumped and delivered by the village leader. Although this system may not be very technically efficient, it entails the presence of some governance structure in the groundwater sector, which is often missing in most groundwater economies, including India (which is now the largest groundwater economy worldwide according to Shah [2009]). We refer to this as *collective well management*. In other villages, wells are owned by individual farmers, and households either pump water from their own wells or buy water from other households that own wells. In either case, households make their own pumping decisions independent of each other. We refer to this as *private well management*. The effectiveness of community-based management may differ under different institutional arrangements since different actors are in charge of managing water and different rules of governance are applied. In this study, we compare the effects of collective well management versus private well management on groundwater resources. Importantly, when we do so, we will take into account the nature of the aquifer.

The rest of the paper is organized as follows. First, we describe the basics of China's well management and the nature of aquifers in northern China, and then formalize hypotheses to be tested later in the paper. In the third

section we describe the survey data and the construction of variables. In the fourth section we present the empirical framework and discuss some estimation issues. In the fifth section we report the estimation results, and in the final section we conclude.

## Well Management and the Nature of Aquifers in Northern China

Groundwater resources play an important role in the economy of northern China. Water availability per capita in the region is only around 300 m<sup>3</sup> per capita, less than one-seventh of the national average and far below the world average (Ministry of Water Resources 2002). Past water projects have tapped almost all of the surface water resources in northern China; with the diminishing supplies of surface water, groundwater has become increasingly important. In 2007, on average, 37% of China's total water supply (industrial, residential and agricultural sectors) comes from groundwater (Ministry of Water Resources 2008). Agriculture relies even more heavily on groundwater; with the exception of rice, at least 70% of the sown area of grains and other staple crops are irrigated by groundwater (e.g. 72% for wheat and 70% for maize, Wang et al. 2007). As a result of this overwhelming dependence on groundwater, groundwater resources are diminishing in large areas of northern China. For example, between 1958 and 1998 groundwater levels in the Hai River Basin (HRB #94), one of the main economic and political centers of China, fell by as much as 50 meters in some of its shallow aquifers, and by nearly 100 meters in some of its deep aquifers (Ministry of Water Resources, World Bank, and AusAID 2001).

### *Different Types of Well Management*

With the growth of China's economy, the availability of water for agricultural use is falling rapidly. Increasing demand for limited water resources from rapidly growing industry and urban populations adds to the existing pressure on the irrigation water supply in the agricultural sector, especially in northern China (Zhang and Zhang 2001). Furthermore, China's government has stated that agricultural users will not be given priority for any additional future allocations of water (China 2002). As groundwater resources have become more scarce, there has also been a simultaneous transition of well ownership in northern China.

<sup>4</sup> Unlike the case of the United States, the de facto rights in rural China are not associated with land ownership or historic use.

Before the rural reforms in the 1980s, the wells in almost all rural villages were collectively owned. As the curator of collective assets, the village leader decided on all aspects of water management: when and where to sink the wells, how many wells to sink, and, importantly, how much water to extract during each season. The village leaders often hire a well operator to pump and deliver water to households under their supervision.

With falling groundwater levels and changes in fiscal policies that weakened the collective ability to invest in maintaining existing wells or sinking new wells, after 1990 the ownership of wells began to shift from collective ownership to private ownership (Wang, Huang and Rozelle 2005). According to a set of survey data that is representative of northern China (and collected by the authors), in 1995 collective ownership accounted for 58% of wells in groundwater-using villages (Wang et al. 2007). By 2004, the share of privately owned wells rose to 70%, shifting a large part of groundwater management into the hands of private individuals.

Changes in well management have the potential to affect the nation's water resources. The characteristics of China's rural villages mean that when village leaders are in charge, as in the case of collective well management, leaders are likely to allocate groundwater among households in a way that takes into account the welfare of all villagers. Although the traditional way of viewing local leaders (which in our case are village cadres; in the Socialist era—1950 to 1984—they were commune or brigade heads) was as authoritarian figures that represented a totalitarian state as its implementer of policy, political scientists and other social scientists working on China have come to a general understanding that this characterization is far from reality. Shue (1988) summarizes the literature and concludes that China's localities were not part of a totalitarian hierarchy, but more a part of a honeycomb of small cellular entities. Each locality was incredibly independent and operated with a great deal of autonomy. Leaders, far from being agents of the state, often acted in ways that insulated localities from upper level government intervention. Leaders implemented policies selectively, disbursed information strategically and generally furthered the interests of their own village rather than those of the state.

Furthermore, several studies (Kung, Cai, and Sun 2009; Rozelle and Boisvert 1994; Zhang 2007) have empirically quantified what others

conclude based on interviews, readings and observations: the decision-making of village leaders is more consistent with agents that care as much about status and other intangible objectives as they do about maximizing profits and implementing policies of the state; leaders care about acting as the village head, protecting and furthering the interests of the village, which leads to higher status and the prestige that comes with such a role. In fact, village leaders often act like traditional village heads or elders of the village that rise to their positions because they care about villagers and are able to help the village solve its problems. Using data through 2000, Zhang (2007) further shows econometrically that village leaders did not gain from their village cadre status in terms of income, assets, consumption, access to off-farm employment for their families or profits for their own businesses. Often they are better off because of their human and physical capital, family background, and other unobservable heterogeneities. Of course there were always self-serving village leaders who were corrupt and exercised power arbitrarily for their own benefit. These stories, however, according to Shue (1988) and Oi (1989), are the exception rather than the norm, and are the ones the media tends to pick up.

There are also reasons to believe village leaders may consider the long-run use of resources. First, leaders are members of the village and they will be living in the village even after they step down as leaders. Their children will live there as well (mobility in China has traditionally been very low). Close kinship and friendship ties could make them take a long-run view. Second, many village leaders—even those facing elections—have been in office for many years. In our sample villages, the average tenure of a village party secretary was 11.4 years (median 9.5 years); the village committee head had an average tenure of 10.4 years (median 9 years). Many of the leaders told the interviewers that they expected to be in office for a long time.

There is an additional question about the feasibility of a leader being able to effectively manage water in a village that is made up of many individuals, each with their own plot. First, the equal distribution of land, the most important production factor in China's villages, makes it easy to for village leaders to allocate water among households (Benjamin and Brandt 2002). Unlike other countries, such as India, land is relatively equally allocated among households in rural China both in terms



of land size and soil quality. The egalitarian nature of land distribution helps avoid the potential distortions and inefficient outcomes that could result under high inequality. The egalitarian nature of land allocation also decreases the probability of the elites capturing land, which the dominance of village leaders would often result in (Mansuri and Rao 2004; Platteau 2004). Second, the structure of rural villages also helps; often, a village is divided into smaller villager groups. The plots of households in each villager group are located together and pump from the same collective well. The leaders of the villager group (also considered village leaders) manage the wells. Third, rural electricity systems are set up such that the supply of electricity can only come from one source, and that source is easily monitored to prevent stealing electricity or tampering with the meters. This means that the use of pumps can be easily monitored. All these characteristics reduce the cost of managing the resource and minimize the potential for conflict (Baland and Platteau 1997, 1998). In short, when village leaders are in charge of managing groundwater, they may tend to behave more like a social planner (as opposed to an individual well owner) and have more of an incentive to internalize the externalities associated with pumping and conserving groundwater for future use when allocating water among households.

In contrast, under private well management, the incentive of households to conserve water may be limited. When wells are privately owned and managed, households either pump water from their own wells (well owners) or buy water from other households that own wells (water buyers). In either case, households make their own pumping decisions independently of other households. Since a water buyer does not even have the de facto rights to groundwater, they would be expected to only seek to maximize their own private benefits, ignoring their externalities or the long run use of the resource. A well owner may have the incentive to conserve water for future use. However, given the typically large number of wells in groundwater-using villages (the average number of wells per village is 75 in our sample areas), the owner's incentive diminishes rapidly as the number of his competitors increases. Furthermore, most wells are owned jointly by a group of individual farmers. The group-owned nature further limits the incentive of well owners to cooperate in investing in groundwater (in our case, conserving water,

Aggarwal 2000). Finally, even if the well owner wants to regulate water use, he is just a fellow villager and neighbor of the village's water users, and does not have the same authority as village leaders, and thus would be less effective in regulating his fellow villagers in water use. This is not unusual. In north Gujarat and parts of south India where the groundwater resource base is already scarce, anarchic groundwater development (unregulated, individually owned groundwater wells) has hastened resource depletion (Moench 1992; Mukherji and Shah 2005). As a result, under private well management, it is entirely plausible that unregulated pumping by individual households could result in the tragedy of the commons, ignoring the externalities that their pumping imposes on other households that withdraw water from the same aquifer.

#### *Nature of Aquifers*

Partly because the shift to private well management during the 1990s coincided with the rapid decline of water levels in aquifers, scholars have blamed private well management for the *accelerated* decline in groundwater levels in northern China (Zhang and Zhao 2003).<sup>5</sup> Indeed, if collective well management produced sustainable extraction while private well management resulted in the tragedy of the commons, economic theory would also indicate that the rise of private well management was at least one of the causes of the more rapid depletion of groundwater resources. However, in one of the few empirical studies on this subject, Wang, Huang, and Rozelle (2005) show that groundwater levels were not lower in the villages in which wells were managed by private owners. Their results suggest that, at least, there is no evidence that indicates private well management depletes groundwater more than collective well management does.

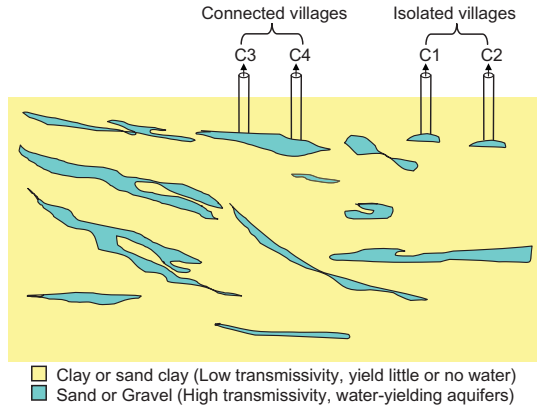
<sup>5</sup> The Ministry of Water Resources of China uses the level of overexploitation (i.e. the amount of groundwater extraction in excess of the amount of recharge) to determine whether groundwater management is needed (Ministry of Water Resources 2003). As a result, most debates inside China have been based on declining water levels. The methodology used by the Ministry of Water Resources is a subject of much discussion and criticism, since abstraction exceeding the recharge level (and consequently declining water levels) does not necessarily mean mismanagement. Given the absence of a better methodology, however, we will use it in the discussion here. It should be noted that in our analysis comparing pumping behavior among users (collective vs. private; connected vs. isolated aquifers), we did not use the differences in depth to water as the comparison criterion. Instead, depth to water was used as one of the control variables (see table 4). We compare water use at the plot level.

When trying to explain why there is little difference between collective well management and private well management in terms of their effects on groundwater, we believe the hydrology of the aquifers may play a key role. What observations could have led us to such a hypothesis? During a field trip to one of the most water-short counties in the HRB, a leader complained that households in his neighboring villages were “stealing” groundwater *from his village*. He believed that groundwater was flowing laterally from the aquifer under his own village into the command area of a well that rural residents had sunk in the neighboring village. The leader also told us that he would have sunk a new well of his own to compete with the well in the neighboring village in extracting groundwater, had his village had enough capital to do so.

Such anecdotes suggest that the nature of the aquifer may affect the behavior of village leaders. If water in an aquifer is accessible not only to the village above the aquifer but also to neighboring villages, the water level in one village may be affected by the pumping of neighboring villages and vice versa. If this were the case, we could say that the aquifers underlying different villages are *connected*. In the rest of the paper, we will call a village whose aquifer is connected to those of neighboring villages a *connected village*, and a village that is hydrologically isolated from other villages an *isolated village*. An illustration of connected and isolated villages is shown in figure 1. In connected villages, instead of being assured that water not used during a specific period is available in future periods (as in isolated villages), leaders need to worry about what their neighbors will be doing because water left in the aquifer this period may be pumped away by them, and thus no longer available in future periods.

### Hypotheses

Theoretical models that predict how the connectedness of aquifers would affect pumping behavior have been presented in the literature (Dixon 1991; Negri 1989; Saak and Peterson 2007); often, a feedback Nash game is used to model the behavior. Eswaran and Lewis (1984) showed that when there is seepage of the resource (e.g. oil fields) between two or more fields (i.e. the fields are connected), a greater proportion of the existing stock is extracted each period. Similar results can be found in Levhari and Mirman (1980). Saak and Peterson (2007) have proven that when



**Figure 1. Illustration of isolated and connected villages**

*Note:* Here we draw a simplified version of figures 8 and 9 in Wang et al. (2008) for the purpose of illustrating isolated and connected villages in our analysis. Most villages pump from the sand or gravel aquifers that yield large volumes of water. Moreover, the sizes of these water-yielding aquifers differ, and can range from less than 200 km<sup>2</sup> to more than 2000 km<sup>2</sup> (Chen 1999). The size of a village in our study area ranges from less than 1 km<sup>2</sup> to more than 10 km<sup>2</sup>. For a small water-yielding aquifer, there may only be one single village lying above it, which is the case of village C1 and village C2. Then such a village (either C1 or C2) is practically isolated from other villages hydrologically since it is difficult for its water to flow through clay into the aquifers of other villages. Other villages (e.g. village C3 and C4) may be located above a large water-yielding aquifer. Then these villages are practically sharing a common aquifer with each other. In this case groundwater is more akin to a common property resource.

there are lateral groundwater flows between the wells of two farmers, and when farmers are not regulated, each farmer will pump more than the efficient level (defined as the pumping rate each individual farmer would choose to maximize his individual benefit when the wells were not connected). Their work also shows that the result does not change if farmers have complete or incomplete information about the speed of the flow. Negri (1989) further shows theoretically that a water user may extract more than what he would have had there been no competition among users to discourage the extraction of other users. This strategic behavior would exacerbate the inefficient extraction of groundwater resources.

Applying the theoretical results to the case of a connected village means when recognizing the correlation between the water level in his village and the pumping by neighboring villages, a village leader might begin to compete with other villages when extracting groundwater. It is as if the leader is involved in a difference game with other villages. Then the connectedness of villages—even when the wells are managed by village leaders—could lead to the inefficient use of groundwater

resources. Following the above argument, we can state hypotheses that examine how water use changes if the nature of the aquifer is either isolated or connected:

**Hypothesis 1a:** Suppose one household is in an *isolated* village and another household is in a *connected* village. Both households use groundwater allocated by the village leader in a village that is under *collective* well management. Further suppose that the two villages and underlying aquifers are the same in other aspects (e.g. same level of groundwater stock, same number of wells, same well yields). Under such a set of assumptions, the households in the connected village will be allocated more water than the household in the isolated village.

Similar arguments can be made for villages under private well management. In connected villages, in addition to the presence of other competing water users within the village, the connectedness of aquifers further undermines the incentive of users (either well owners or water buyers) to conserve water.

**Hypothesis 1b:** Suppose one household is in an *isolated* village and another household is in a *connected* village. Both households decide how much groundwater to obtain from *privately* owned and managed wells. Further suppose that the two villages and underlying aquifers are the same in other aspects (e.g. the same level of groundwater stock, same number of wells, same well yields). Under such a set of assumptions, the household in the connected village will use more water than the household in the isolated village.

Theoretical models that examine how water use changes when wells are managed collectively by the village leaders or privately by individual households have also been studied in the framework of optimal control versus competitive groundwater pumping (e.g. Gisser and Sanchez 1980; Provencher and Burt 1993; Rubio and Casino 2003; Rubio and Casino 2001). Under either collective or private well management, the agent (the village leader or individual household) will pump water to the point where its marginal cost equals marginal benefit. Under private well management, each household only maximizes his own profits and

thus will only consider its own private cost and ignore the externality of his pumping on other households. In contrast, under collective well management, village leaders maximize the income of the village. In order to achieve this goal, the village leader will make each household internalize the externality by equating its marginal benefit with its marginal social cost. Of course, the degree to which leaders can exert control over villagers depends on the prevailing institutional conditions, the level of monitoring, and transaction costs. Lopez (1998) empirically examines the effectiveness of village controls by estimating and then testing the parameter that measures the fraction of the external/social cost that individual cultivators internalize in their land allocation decisions. Under certain reasonable assumptions,<sup>6</sup> it can be shown that the higher is the fraction of social cost being internalized, the lower is the pumping level, *ceteris paribus*. Therefore, we can examine the difference between collective and private well management through the following hypotheses:

**Hypothesis 2a:** Suppose one household is under private well management and another household is under collective management; both households are located in isolated villages. Further suppose that the two villages and underlying aquifers are the same in other aspects (e.g. the same level of groundwater stock, same number of wells, same well yields). Then the volume of water pumped by the household under private well management will be higher than the volume of water allocated to the household under collective management.

**Hypothesis 2b:** Suppose one household is located in a village under private well management and another household is in a village under collective management. Both households are located in connected villages. Further suppose that the two villages and underlying aquifers are the same in other aspects (e.g. the same level of groundwater stock, same number of wells, same well yields). Then the volume of water pumped by the household in the village under private well management will be higher than the volume of water allocated to

<sup>6</sup> The most important assumption is that the periodic benefit of a household net of the cost of other inputs is concave in the level of pumping. It is also assumed that households under private well management and households under collective well management have the same benefit functions.

the household in a village under collective well management.

Empirically, the difference between private and collective well management may not be significant. A well-known result established by Gisser and Sanchez (1980) and probably illustrated more clearly in Rubio and Casino (2001, 2003) is that the difference between the socially optimal exploitation and the private exploitation of the aquifer (represented by a feedback equilibrium in Rubio and Casino [2001, 2003]) decreases with the storage capacity of the aquifer, and thus if it is relatively large the two equilibria are identical for practical purposes. As a result, in most situations the benefits from managing groundwater are numerically insignificant. In a few cases, the Gisser and Sanchez effect disappears. For example, Koundouri and Christou (2006) analyzed the optimal management of the Kiti aquifer in Cyprus and found that the optimal control significantly increased social welfare by 409.4%. Such a large gain from management is attributed to the near-depletion of the aquifer under consideration. The magnitude of the benefit from managing groundwater is

also sensitive to other parameters such as the discount rate, the water demand schedule and energy prices (Feinerman and Knapp 1983; Kim et al. 1989; Pitafi and Roumasset 2009; Worthington, Burt, and Brustkern 1985).

### Data Description

The data used in the study come from the 2004 China Water Institutions and Management (CWIM) Survey and were jointly collected by the authors. During the CWIM survey we collected data in two provinces in northern China. Hebei Province covers most of HRB and surrounds Beijing, and Henan Province is located in the middle reaches of the Yellow River Basin (figure 2). These two river basins are two of the nine major river basins in China. The climate in the surveyed area is semi-arid. From the foot of the mountains (in western Hebei) to the coastal area, Hebei Province can be divided into an alluvial flood plain (western part); a flood and lake sedimentary plain (middle part); and an alluvial coast plain (eastern part—figure 2 in Foster et al. 2004). Most relevant to our analysis, transmissivity varies

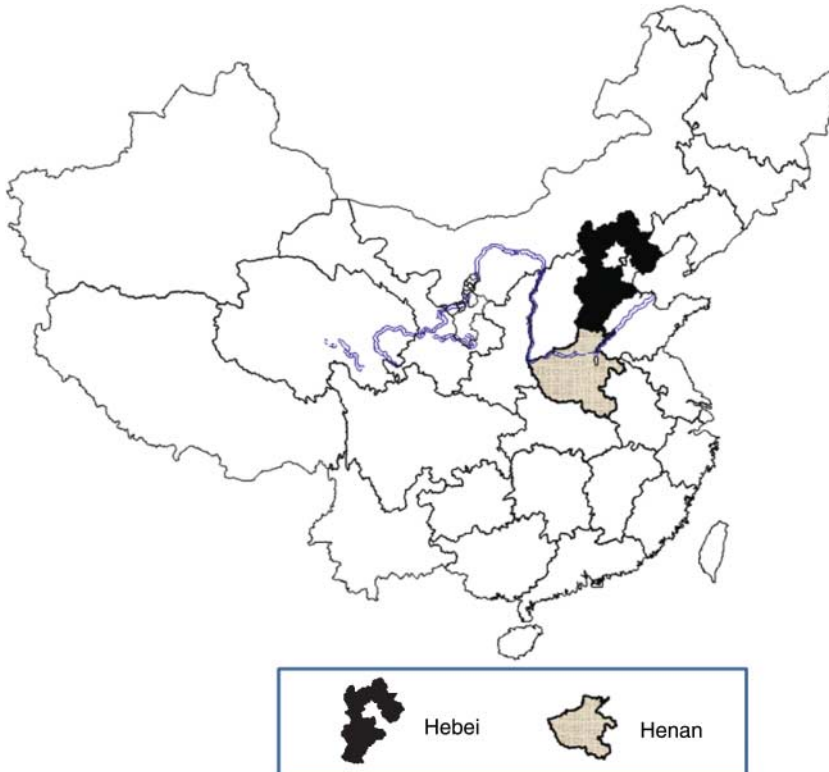


Figure 2. The map of China and the study areas



greatly across different parts of the aquifers in both the Hebei and Henan Provinces (Chen 1999; Foster et al. 2004; Wang et al. 2008). Variations in transmissivity are mostly due to variations in the thickness of aquifers, as well as types of materials (e.g. sand, gravel or clay) in different parts of aquifers (Wang et al. 2008). As a result, aquifers in the study area cannot be characterized as bathtub or single-cell aquifer, which assumes the instantaneous lateral flow of groundwater between a water user and his/her neighboring users.

In our survey we used a stratified random sampling strategy. The strata are geographic locations that were correlated with the extent of water scarcity. In Hebei Province, one county was randomly selected from each of the three regions: the coastal belt, the most water-scarce area of China; the inland belt, an area with relatively abundant water resources since it is next to the mountains in the western part of Hebei Province; and the region between the coast and mountains. In Henan Province, counties were randomly selected from each stratum that includes irrigation districts with varying distances from the Yellow River. Locations further away from the river are typically associated with increasing water scarcity.

After the sample counties were selected, we then randomly selected 48 villages from these counties. According to our data, five villages only used surface water for irrigation in 2004. In the remaining 43 villages, on average, 87% of the irrigation water came from groundwater. In the rest of the paper we will only include these groundwater-using villages since our focus is on groundwater management. In the CWIM survey, enumerators interviewed three sets of respondents: village leaders, randomly-selected households (between 1–4 households per village), and randomly-selected well managers. Separate survey questionnaires were designed and used for each set of respondents.

A large part of our analyses use data from the household survey. During interviews the enumerators first asked households to list all of their plots, and then on a plot-by-plot basis to recount the plot size, crop mix and irrigation status (whether it was irrigated or whether it was rainfed). From the comprehensive list of plots, we then selected two plots that captured different crops that the households were cultivating, as well as sources of irrigation water. Using a section of the survey that focused solely on the inputs and outputs of these two plots, we were able to collect extremely detailed

information on household crop production and irrigation activities. The enumerators asked households to report yields, crop sale prices, costs and quantities of each type of input, including fertilizer, labor (by production activity), machinery (use of own equipment or rent), pesticides, plastic sheeting, and other inputs.

In our empirical analysis, the plot is used as the basic unit of analysis. Wheat is the major crop grown on most plots during the winter season (planted during the previous October and harvested in June) in Hebei and Henan Provinces. In our sample, about 94% of the sample plots (or 97.6% in terms of sown area) only grew wheat in the winter season. Only a small percentage of the sown area was allocated to other crops, including beans, legumes and cash crops such as oil crops and vegetables. After wheat is harvested, either maize or cotton (competing summer crops) is grown in the summer season (planted in June and harvested in October). In both Hebei and Henan Provinces, the rotation of first wheat and then maize or cotton is the most common cropping pattern. In Henan Province, rice is another major crop grown in the summer season. Most cash crops are also grown in the summer season. Wheat production relies more heavily on irrigation than other crops in the region. This is because the growth of summer season crops (June to October) coincide with the rainy season in the region, while that of wheat does not. For example, in years with abundant rainfall, corn could potentially be 100% rainfed. There is little or no overlap between the irrigation of wheat and that of summer season crops since those crops are usually planted after wheat has been harvested. Since wheat is the major crop that relies on irrigation in the region, we only used the data on the plots that grew wheat in 2004. By doing so, we hold the type of crop constant, and also amass the largest number of observations. In total, there are 196 wheat plots in our data (table 1).<sup>7</sup>

<sup>7</sup> A multi-crop framework could be used to control for the differences in the marginal productivity of water in the production of different crops. We can still justify the use of only wheat plots by using crop season as the unit of time. We can then proceed with theoretical models that have been used in the literature (e.g. Dixon 1991; Negri 1989; Saak and Peterson 2007) to predict how the connectedness of aquifers or the management of wells (collectively managed or privately managed) would affect pumping behavior. The shadow value of groundwater, which captures all future profit flows from groundwater irrigation, would also include the profit flows from irrigating summer season crops. Furthermore, we did not find any large differences in crop mixes between collectively managed villages and privately managed villages, or between connected villages and isolated villages (table 2 of the appendix). So the approach that uses crop season as the unit of time, although a

**Table 1. Type of Plots by Well Management and Connectedness of Aquifers in Hebei and Henan Provinces, 2004**

	Connected Villages	Isolated Villages	Total
Use interview-based measure of connectedness			
Collective	56	24	80
well management	(28.6)	(12.2)	(40.8)
Private	85	31	116
well management	(43.4)	(15.8)	(59.2)
Total	141	55	196
	(72)	(28)	
Use hydrology-based measure of connectedness			
Collective	66	14	80
well management	(33.7)	(7.1)	(40.8)
Private	95	21	116
well management	(48.5)	(10.7)	(59.2)
Total	161	35	196
	(82.2)	(17.8)	

Note: Percentages are reported in parentheses.

Several key variables are constructed from the household survey. The rate of pumping is measured by the volume of water applied on each plot. In villages under collective well management, this is the amount of water that the village leader allocated to each household. In the villages under private well management, this is the amount of water a household pumps itself. To elicit the amount of water use, enumerators asked the household to report for each crop the average length of irrigation time, the total number of irrigations during the entire growing season, and the average volume of water applied per irrigation. We also obtained information from well operators (both collective and private) on the size of the irrigation pump and the average volume of water that each pump was able to pump per hour. This information was useful when households were not clear about the volume of water applied. With data from both households and the well managers, we were able to calculate the volume of water applied on each plot by multiplying the average volume of water that was pumped each hour by the length of time that each plot was irrigated (as reported by the households themselves).

In addition, households reported their expenditure on irrigation water for each crop (and by plot). In almost all villages households

simplified one, would not alter conclusions from the approach that uses year as the unit of time and models multiple crops, including wheat as well as summer season crops.

paid for water according to the number of hours that the managers operated the pumps to irrigate their plot. Therefore, the cost of water is closely related to the energy cost that was needed to lift water out of wells (either electricity or diesel). The cost of water is calculated as total payment for water divided by the volume of pumping.

To construct another key variable, well ownership/management, for each groundwater-using plot, we asked households to define the ownership of the wells from which they obtained groundwater for irrigation: does it belong to the household himself/herself, does it belong to another household (that is, a private well owner) or does it belong to the collective? We then defined well ownership/management based upon their answers.

Although the general hydrogeological structure of the study area is well studied (Chen 1999; Foster et al. 2004; Wang et al. 2008), location-specific data (village level) that describe the hydraulic properties of the aquifer are not available. To explore the link between the nature of the aquifer and the rate of pumping, we use two sets of measures in our analysis. The first set, the *interview-based measure of connectedness*, was constructed from responses of village leaders to two questions asked in the 2004 CWIM survey: "Do you think pumping by households/village leaders in neighboring villages will affect the water level in your village," and "Do you think your own pumping (or that of households in your village) will affect the water level in neighboring villages?" Of the 43 surveyed villages in the Hebei and Henan Provinces, 26 village leaders answered yes to both questions. Three village leaders answered yes to the first question but no to the second question. If a village leader answered yes to the first question, we defined the village as a *connected village*. If a leader answered no, we defined the village as an *isolated village*.<sup>8</sup>

<sup>8</sup> The editor correctly pointed out that if water users are myopic and the pumping in one well does not cause a very immediate drawdown in neighboring wells (i.e. no intra-village connectedness), then inter-village connectedness does not play a role. In our survey, we asked well managers the following question to see if intra-village connectedness existed: "Does pumping in your neighboring wells affect the water level in your well?" In only 9 villages did well managers answer no. The majority of the villages (34 out of 43) have intra-village connectedness. Connected villages are more likely to have intra-village connectedness, probably due to the general hydraulic property in the area. All 26 connected villages have intra-village connectedness. All 9 villages with no intra-village connectedness are isolated villages. In addition, we find that intra-village connectedness is also related to well density. The well density is 31 wells per 1,000 mu in villages whose well managers reported

Although the village leader's answer may have differed from the actual connectedness of the aquifers, since it is their perception upon which they rely to guide their actions/decisions, we believe this way of categorizing villages is reasonable. This is also consistent with the status quo in rural China, where the formal regulatory framework is weak and hydrologists are not involved in groundwater management. As a result, when making decisions regarding groundwater, water users only have their own perceptions of the aquifer characteristics to rely on, which they form from their own observations of past histories of water levels and pumping rates. Similarly, Shah (2009) also observed that in India farmers' decisions and actions are guided more by their own theories about the aquifers than by formal science.

Although reasonable, the use of the interview-based measures of connectedness may cause some potential problems. For example, reporting bias may arise if village leaders strategically report that the aquifer is connected in order to shift the blame for mismanagement. Therefore, we also used an alternative measure of connectedness based on the evaluation of an independent hydrologist.<sup>9</sup> Our hydrological consultant relied on three sets of information to determine whether villages were connected or isolated. First, hydrological records that had been put into geo-referenced maps were consulted from the literature (Chen 1999; Foster et al. 2004; Wang et al. 2008). Based on this, the consultant and his working group were able to determine the general nature of the aquifer in the areas our sample villages are located in. For example, although location-specific data on storativity and transmissivity are not available, our hydrological consultant could easily identify, using geo-references maps, those isolated villages that are hydrologically isolated from other aquifers by an aquitard. Vertically, aquifers in Hebei Province are divided into four layers, with unconfined groundwater in the first layer and confined groundwater in the second, third and fourth layers (the Quaternary Formation, Chen 1999; Foster et al. 2004; Wang et al. 2008). Thus, if a village is pumping from the unconfined aquifer while neighboring villages are pumping from the second layer

(or vice versa), this village is isolated because it is difficult for water to flow through clay that separates the unconfined layer and the second layer. Aquifers in Henan province also occur in multi-layers, a top unconfined layer, a middle semi-confined layer, and a bottom confined layer (Manouchehr et al. 1996). This has also created some isolated villages in Henan Province.

Second, the consultant and his survey team also contacted personnel in the county-level water resource bureaus (irrigation divisions) and worked with them to identify the nature of the aquifers that serviced each of the villages. Finally, the survey team personally visited these county-level water resource bureaus, executing a survey and interviewing the staff. The consultant's survey team also visited the sample villages. Accompanied by county-level water resource bureau personnel, the consultant's survey team relied on interviews, local hydrology information and other sources of information to help understand the nature of the aquifer under each sample village. For example, if a village is *connected*, it pumps water from the same aquifer as neighboring villages. In most connected villages, both county-level water resource bureau officials and village leaders told the hydrological consultant that wells sunk in different villages had the same static water level (the level of water in a well before any pumping occurs), a strong indication that villages in the area are pumping from the same aquifer. Based on these information sources, the consultant categorized each village as either a connected village or an isolated village. This variable is named *hydrology-based measure of connectedness*.

A cross-check showed that the correlation coefficient between the hydrology-based measure and the interview-based measure was as high as 0.75. This means that village leaders were able to accurately (at least relative to a hydrologist) assess if their villages were connected or isolated.<sup>10</sup> Another piece

intra-village connectedness, and 15 wells per 1,000 mu in other villages.

<sup>9</sup> We want to thank the editor and the reviewers for urging us to create the alternative measure that has strengthened our results significantly.

<sup>10</sup> In those villages that were identified as connected, the hydrological consultant first asked the village leaders to list the names of neighboring villages whose pumping affected their water levels. All village leaders listed the names without any difficulty. In fact, in one village, the leader responded that only pumping by villages to the north and south influenced his water level. Villages to the east and the west were pumping from a different layer of aquifer and thus did not influence water levels in the village. The hydrological consultant then asked the village leaders how soon they could feel the impact of the pumping by neighboring villages. In most villages, leaders reported that the impacts were felt within the same irrigation season. They observed that their water levels dropped faster when neighboring villages were pumping.

**Table 2. Variable Definitions**

Collective-Connected	Interaction dummy (= 1 if a plot is irrigated by water from a <i>collectively</i> owned and managed well and is located in a <i>connected</i> village)
Private-Isolated	Interaction dummy (= 1 if a plot is irrigated by water from a <i>privately</i> owned and managed well and is located in an <i>isolated</i> village)
Private-Connected	Interaction dummy (= 1 if a plot is irrigated by water from a <i>privately</i> owned and managed well and is located in a <i>connected</i> village)
Collective-Isolated	Interaction dummy (= 1 if a plot is irrigated by water from a <i>collectively</i> owned well and managed and is located in an <i>isolated</i> village)
Water cost, log	Log of water cost measured in yuan/m <sup>3</sup>
<i>N</i>	Number of households the well irrigates
Well density	Density of wells (# of wells per mu of sown area)
Amount SW	Volume of surface water applied on the plot measured in m <sup>3</sup> /mu
Num Lack	Number of years that there was not enough water in the wells in the past three years
Crop price, log	Log wheat price households received for crop sales in yuan/kg
Fertilizer price, log	Log of fertilizer price measured in yuan/jin. 1 jin = 0.5 kg
Drought-tolerant	A dummy variable (= 1 if drought-tolerant variety was planted on the plot)
Sand	A dummy variable (= 1 if soil type is sand and 0 if soil type is loam or clay)
Plot size, log	Log of plot size in mu
Distance	Distance from the plot to the well measured in km
Lined	Percentage of the conveyance route that is lined, %
Irrigation method	A dummy variable (= 1 if the plot is irrigated using flooding)
Age	Average age of household members that farmed in the household
Education	Average years of schooling of household members that farmed in the household
Hired labor	Percentage of hired labor used on the plot, %

Note: Mu is the metric unit of land area that is used in China. 1 mu = 1/15 hectare.

of evidence comes from the positive correlation between general transmissivity, which the hydrological consultant relied on to construct the hydrology-based measure, and the interview-based measure of connectedness. In Hebei Province, the second layer aquifer has higher transmissivity than the top, unconfined aquifer (The Institute of Hydrogeology and Environmental Geology, Chinese Academy of Geological Sciences 2007). This is because the second layer aquifer is thicker and has a larger grain size. Most villages in Tang County (located along the inland belt next to the hills and mountains that rise in the western part of Hebei Province) pump from the top unconfined aquifers (depth to water in wells ranges from 12–27 meters). Most villages in Xian County (located in the coastal area in the eastern part of Hebei Province) pump from the second-layer aquifer (depth to water in wells ranges from 70–100 meters); aquifers in Xian County generally have higher transmissivity than those in Tang County. This is consistent with the observation that the percentage of connected villages (using the interview-based measure) is much higher in Xian County than in Tang county (75% versus 33%). In the empirical analysis we will use both sets of measures as a robustness check.

## Estimation

The empirical objective is to estimate the following equation and use the estimation results to examine the effects of different types of well management and the nature of the aquifer on the rate of water use ( $w$ ):

$$(1) \quad \ln w = \beta_0 + \beta_1 \text{ Collective-Connect} \\ + \beta_2 \text{ Private-Isolated} \\ + \beta_3 \text{ Private-Connected} \\ + \beta_4 \text{ Cost}_{\text{Water}} + \mathbf{M}\gamma + \varepsilon,$$

where  $\varepsilon$  is the error term. The dependent variable,  $w$ , is in log form. Table 2 lists the definitions of each explanatory variable, and summary statistics are reported in table 1 of the appendix.

The key independent variables are generated using two sets of dummy variables. The first set is two aquifer dummy variables: the Connected dummy equals one for a connected village and zero otherwise; the Isolated dummy equals one for an isolated village and zero otherwise. Our data indicate that the nature of the aquifer varies across places. Using the hydrology-based measure of



**Table 3. Water Cost and Some of the Relevant Factors**

Dependent Variable: Water Cost Measured in Yuan/m <sup>3</sup>				
	(1)		(2)	
	Use Interview-based Measure of Connectedness		Use Hydrology-based Measure of Connectedness	
Depth to water in well measured in meters	0.00519***	(0.00122)	0.00543***	(0.00140)
Electricity price in Yuan/kwh	0.732	(0.794)	0.838	(0.849)
Flow rate of pump measured m <sup>3</sup> /hour	-0.00215**	(0.000839)	-0.00208**	(0.000822)
Dummy, = 1 if used centrifugal pump and diesel engine	0.153	(0.124)	0.159	(0.129)
Share of sown area irrigated by surface water in the village in year 2001, %	-0.000958	(0.000620)	-0.000907	(0.000576)
Dummy, = 1 if plot is located in a connected village	-0.00970	(0.0406)	0.0351	(0.0561)
Dummy, = 1 if plot irrigated by water from own well	-0.156	(0.317)	-0.277	(0.387)
Dummy, = 1 if plot irrigated by water purchased from privately managed well	-0.148	(0.327)	-0.263	(0.395)
Dummy, = 1 if plot irrigated by water from collectively managed well	-0.192	(0.329)	-0.308	(0.397)
Distance	0.0000535	(0.0000469)	0.0000523	(0.0000492)
Age	-0.00195	(0.00163)	-0.00180	(0.00158)
Education	-0.0101	(0.00861)	-0.00959	(0.00835)
County fixed effects	Yes		Yes	
Number of observations	195		195	
Adjusted R <sup>2</sup>	0.488		0.490	

Note: Standard errors in parentheses (clustered at the village level); \*, \*\*, \*\*\* significant at the 10%, 5% and 1% level, respectively.

connectedness, more than 80% of the sample plots are located in connected villages and other plots are in isolated villages (table 1). The second set of dummy variables is two ownership/management dummies: the Collective dummy equals one if the plot is irrigated by water from a collectively owned and managed well and zero otherwise; the Private dummy is the opposite of the Collective dummy. Among the 116 wheat plots, almost 60% draw water from privately managed wells (table 1). This is consistent with the increasing trend of well privatization that is ongoing in northern China (Wang et al. 2006).

We then create a set of interaction terms between the aquifer dummy variables and the ownership/management dummy variables. These interaction terms define four groups of plots. A Collective-Isolated plot is a plot that is located in an isolated village and is irrigated by water from a collectively managed well. A Private-Isolated plot is irrigated by water from a privately managed well and is located in an isolated village. Similarly, a Collective-Connected (Private-Connected) plot is irrigated by water from a collectively (privately) managed well and is located in a connected village. All four groups of plots are present in

our sample. Using the hydrology-based measure, more than 40% of the sample plots are Private-Connected plots (table 1). Approximately 30% are Collective-Connected plots, 10.7% are Private-Isolated plots, and 7.1% are Collective-Isolated plots. The base group in equation (1) are Collective-Isolated plots.

We also control for the cost of water. Table 3 reports a county fixed effect model that examines how the cost of water relates to a set of factors. The estimated coefficient on the depth to water in wells is positive and statistically significant. A large part of variation in the cost of water is driven by the differences in the depth to water in wells across space. For example, in Hebei Province, wheat-growing households in the fourth quartile of depth to water (the households pumping from the deepest wells) paid as much as 0.50 yuan/m<sup>3</sup> for water; those households in the first quartile paid as little as 0.07 yuan/m<sup>3</sup>.<sup>11</sup> Since the depth to water in wells is probably closely related to the level of

<sup>11</sup> Yuan is the unit of currency used in China. One U.S. dollar was about eight yuan in 2004 and dropped to about seven yuan in 2008.

groundwater stock in the aquifer, and the cost of water is closely related to the depth to water, by including the cost of water in the estimation, the effect of groundwater stock is controlled for.<sup>12</sup>

Costs of water are also related to energy prices and pump parameters such as flow rate and pump type (table 3). The estimated coefficient on electricity price has the expected positive sign since higher energy prices increase pumping costs. The estimated coefficient, however, is not statistically significant. This is because electricity prices mostly vary between counties, not within the same county. The average price of electricity is 0.57 yuan/kwh in the sample area. In 4 of the 9 sample counties, all households received exactly the same electricity price. In the other 5 counties, the standard deviation is less than 0.071 yuan/kwh. The flow rate of the pump is a significant determinant of the cost of water. The estimated coefficient is negative and statistically significant. The flow rate of the pump is highly related to the diameter of the outlet pipe. Most pumps in our sample areas had either a 3-inch or 4-inch pipe; a 4-inch pipe has a larger flow rate (66 m<sup>3</sup> per hour on average, where a 3-inch pipe allows 45 m<sup>3</sup> per hour). We observed both electric and diesel engines in the sample areas. Diesel engines are used only in shallow wells with depths to water less than 16 meters. Diesel engines are also mostly used in centrifugal pumps. Electric pumps are used in both shallow and deep wells, and are often submersible. In the regression, the estimated coefficient on the dummy that equals one for centrifugal pump and diesel engine is positive. This is because diesel is generally more expensive than electricity. *Ceteris paribus*, the cost of pumping is higher using a pump with a diesel engine than a pump with an electric engine.

The vector **M** represents a list of control variables that may affect the rate of pumping. The price of wheat that households have received during sales and the price of fertilizer are included to control for the benefit of pumping groundwater. Three additional sets of variables are included in the vector **M**. The first

set of variables controls for plot characteristics, including soil type (whether is it sandy soil or not), whether a drought-tolerant variety was planted, the size of the plot, distance from the plot to the well measured in kilometers, whether households use flood irrigation or not and the percentage of conveyance distance that is lined. The second set of variables controls for household characteristics, including the average age and education of the on-farm labor of a household and percentage of labor that is hired. The third set of variables controls for the characteristics of water resources and wells in the village, including the volume of surface water applied on the plot, the number of years that there was not enough water in the wells during the previous three years, the number of households that use a well, and the density of wells measured in the number of wells per unit of sown area in the village. We also use county fixed effects through a set of county dummies.

A potential econometric issue is the endogeneity of the well management. If a household wants to pump more water, it may choose to obtain water from a privately owned well so that it is not subject to regulation by the village leader. If this is the case, the type of well management and the rate of pumping may be simultaneously determined; then well management may be endogenous. To address this issue, we instrument for well ownership using the following five variables: a dummy variable that equals one if there were policy efforts by upper level government to encourage private wells (e.g. whether the upper-level government organized meetings or issued directives, whether the government provided fiscal subsidies for investment in wells); household asset per capita; household land per capita; the share of groundwater irrigated area in the household in 2001; and whether land was reallocated between 2002 and 2004. The policy of upper level governments has been shown to have played an important role in the sharp shifts away from collective management (Wang, Huang, and Rozelle 2005). Household asset per capita affects the ability of a household to invest in sinking a well. Both household land per capita and the share of groundwater irrigated area in the household measure the need of a household for a well to access groundwater. In some rural areas, land was reallocated so that plots of the same household are located together to facilitate irrigation, including the construction of wells (Ma 2008). All five variables are correlated with well ownership (propensity to sink a well), but they are not likely to be

<sup>12</sup> The simplifying assumption that the depth to water in wells is closely related to the level of groundwater stock is commonly used in the literature on the economics of groundwater. This is because the largest impact that a drop in the groundwater stock has on users is probably the increase in pumping cost, which is captured by the increase in the depth to water. In fact, some studies have modeled the change in the level of groundwater stock as the change in the depth to water in wells (e.g. Brozović et al. 2006; Feinerman and Knapp 1983).

correlated with the dependent variable or the volume of water use. So they could potentially serve as instrumental variables (IVs) for well ownership.

Since only dummy variables (interaction terms of the aquifer dummies and ownership dummies) are used, the measured effects of the type of well management and the connectedness of aquifers on water use could also be due to some unobservable factors. It is possible that connectedness is correlated with location in some unobserved way that influences agricultural productivity. We have examined four variables that are related to agricultural productivity. The first variable, soil type, measures whether a plot has sandy or other types of soil (loam or clay). The second variable, soil quality, is a dummy variable that equals one if a farmer rates the soil quality of the plot as above-average (compared to other plots in the village). The third variable, water quality, equals one if the village leader considers groundwater in the village to be of good quality. Both soil and water quality are subjective measures. The fourth variable measures the percentage of cultivated land in the village that has saline-alkaline soil. We conducted a simple  $t$  test on each of the four variables. In all four tests, we failed to reject the null hypothesis that the mean of the variable is not different between connected and isolated villages. The  $p$ -values of all four  $t$  tests are larger than 0.4. In other words, we do not find any empirical evidence that connectedness is correlated with factors that influence agricultural productivity. We do not find any large differences in crop mixes between connected villages and isolated villages either (table 2 of the appendix).

There may also be some characteristics of aquifers that affect water usage and are also correlated with the RHS variables in the regression. For example, connected aquifers may have higher well yields. There may also be unobservable characteristics of villages with remaining collective wells that lead them to be better at conserving water than privately-operated wells. One such factor is the shared values or community cohesion, which has been reported to be a major determinant of collective action. Not controlling for unobservable factors could affect our results. For example, if areas with high well yields were those that were kept by the collective (and private wells were more likely to be new wells drilled by individual farmers because water yields were too low in the original collective wells), and high well yields led to more water use, then

the omission of well yields would lead to an upward bias in the estimated coefficient on the variable *Collective-Connected*. Although the use of county fixed effects helps control for any unobservable factors at the county level, we do not have measures of those unobservable factors at the village level; nor do we have a set of panel data to control for the unobservable factors. This limits the inferences we can draw from data and the ability to test the hypotheses.

## Results

Table 4 reports the empirical results. Equation (1) is estimated using both the interview-based measures of connectedness (table 4, columns 1 and 2) and the hydrology-based measures of connectedness (columns 3 and 4). In addition to using OLS (columns 1 and 3), we also implement the instrumental variable estimation that addresses the endogeneity of well ownership (columns 2 and 4). Specifically, we use the two-step feasible generalized method of moments (GMM) since it generates more efficient results than 2SLS. We implemented the Sargan-Hansen test and Stock and Yogo test (both available in STATA command `ivreg2`). Results indicate that instruments are valid, and our model is not weakly identified. The latter is confirmed by results from the first stage regressions of the IV/GMM estimation (results not reported for the sake of brevity). For example, for one of the endogenous variables, *Private-Connected*, the estimated coefficient on the policy variable and the land reallocations variable are both positive, large in magnitude and statistically significant; the adjusted  $R^2$ s are 0.594 (interview-based measure) and 0.409 (hydrology-based measure).

All four models performed well (table 4, columns 1–4). The adjusted  $R^2$ s range from 0.226 to 0.456. The estimated coefficients on most control variables have the expected signs. Most notably, the coefficient on the cost of water is negative and statistically significant. The estimated coefficient on wheat prices is not statistically significant in any specifications. This is probably because there is not much variation in crop prices across sample households. In 22 out of 48 villages, all sample households reported exactly the same price of wheat. Other results are also intuitive. The estimated coefficient on the volume of surface water applied on the plot has the expected

**Table 4. The Effect of Well Management and Connectedness of Aquifers on the Rate of Pumping**

Base group:	Dependent Variable: Log of the Volume of Water Pumped per mu, m <sup>3</sup> /mu							
	Use Interview-based Measure of Connectedness				Use Hydrology-based Measure of Connectedness			
	(1) OLS		(2) IV/GMM <sup>a</sup>		(3) OLS		(4) IV/GMM <sup>a</sup>	
Collective-Isolated								
Collective-Connected	0.258***	(0.0704)	0.362*	(0.188)	0.235**	(0.106)	0.419**	(0.154)
Private-Isolated	0.220***	(0.0626)	0.681***	(0.213)	0.220***	(0.0773)	0.544**	(0.242)
Private-Connected	0.362***	(0.0820)	0.698***	(0.158)	0.353***	(0.116)	0.775***	(0.160)
Water cost, log	-0.175***	(0.0358)	-0.176***	(0.0352)	-0.186***	(0.0387)	-0.185***	(0.0385)
N	-0.000441	(0.000691)	-0.000893	(0.000870)	-0.0000836	(0.000649)	-0.000491	(0.000873)
Well density	-2.063*	(1.101)	-2.952*	(1.508)	-1.580	(1.171)	-3.130*	(1.470)
Amount SW	-0.0000407	(0.000190)	-0.0000546	(0.000180)	-0.000118	(0.000212)	-0.0000734	(0.000198)
Num Lack	-0.0346*	(0.0173)	-0.0115	(0.0216)	-0.0396	(0.0235)	-0.0387	(0.0329)
Crop price, log	-0.227	(0.538)	-0.699	(0.713)	-0.302	(0.504)	-0.580	(0.640)
Fertilizer price, log	-0.0438	(0.0501)	0.00969	(0.0598)	-0.0449	(0.0513)	0.00970	(0.0571)
Drought-tolerant	-0.0904***	(0.0316)	-0.108**	(0.0412)	-0.0897**	(0.0343)	-0.0958**	(0.0434)
Sand	0.0436	(0.0310)	0.0399	(0.0481)	0.0347	(0.0317)	0.0182	(0.0470)
Plot size, log	-0.0541**	(0.0230)	-0.0692**	(0.0237)	-0.0446*	(0.0226)	-0.0547*	(0.0258)
Distance	0.0000833	(0.0000914)	0.000165	(0.000141)	0.0000103	(0.000103)	0.0000357	(0.000110)
Lined	0.000592	(0.000579)	0.000425	(0.000687)	0.000597	(0.000622)	0.000519	(0.000575)
Irrigation method	0.0429	(0.0430)	0.0217	(0.0376)	0.0508	(0.0396)	0.0308	(0.0331)
Age	-0.00114	(0.00192)	0.000251	(0.00256)	-0.00149	(0.00215)	-0.000988	(0.00298)
Education	-0.00160	(0.00765)	0.00584	(0.0126)	-0.00317	(0.00864)	0.00509	(0.0126)
Hired labor	-0.000782	(0.00139)	-0.00232*	(0.00131)	-0.000155	(0.00144)	-0.00102	(0.00143)
Constant	5.567***	(0.238)	5.634***	(0.439)	5.593***	(0.245)	5.574***	(0.408)
County fixed effects	Yes		Yes		Yes		Yes	
Number of observations	196		196		196		196	
Adjusted R <sup>2</sup>	0.456		0.226		0.427		0.254	

Note: Standard errors in parentheses (clustered at the village level); \*, \*\*, \*\*\* significant at the 10%, 5% and 1% level, respectively.

<sup>a</sup>Five variables are used to instrument for well ownership: a dummy variable that equals one if there were policy efforts by upper level government to encourage private wells (e.g. whether the upper level government organized meetings or issued directives, whether the government provided fiscal subsidies for investment in wells); household asset per capita; household land per capita; the share of groundwater irrigated area in the household in 2001; and whether land was reallocated between 2002 and 2004.



negative sign. If households had used more surface water, they would have demanded less groundwater. This is particularly true in our sample area. More than 75% of households responded that they preferred surface water to groundwater. This is because surface water is often cheaper than groundwater in the area. However, the estimated coefficient is not statistically significant. This is probably because only 24 out of 196 plots used any surface water in addition to groundwater. If a drought-tolerant plant was raised on the plot, less water was used (coefficient is negative and statistically significant).

Results are also robust regarding the definition of connectedness (interview-based or hydrology-based measures). The signs and the significance levels of estimated coefficients for most variables do not change between columns 1 and 3 (or between column 2 and 4). The sizes of the estimated coefficient are also well within the same order of magnitudes. Most importantly, the results on the key parameters of interest are robust. Tests across equations show that the estimated coefficients on Collective-Connected in columns 1 and 3 (or columns 2 and 4) are not statistically different. The same conclusion holds for the estimated coefficients on Private-Isolated and Private-Connected.

As expected, the standard errors from the IV/GMM estimation are larger relative to when OLS is used. The magnitudes also change; when IV is used, the estimated coefficients on Collective-Connected, Private-Isolated and Private-Connected are all larger, using either the interview-based or the hydrology-based measure of connectedness.

Estimation results on the key parameters of interest show that the connectedness of the aquifer does have a significant effect on the rate of pumping. Since the dependent variable is the log of the volume of water pumped per mu, and the base group in is a Collective-Isolated plot, the coefficient on the interaction term, Collective-Connected, measures the percentage difference in the rate of pumping between a Collective-Connected plot and a Collective-Isolated plot (table 4, row 1).<sup>13</sup> Furthermore, since the dependent variable is in log form and the independent variable is a dummy variable, the *exact* percentage difference is calculated as  $\exp^{\beta} - 1$ , where  $\beta$  is the parameter on

the dummy variable (Halvorsen and Palmquist 1980). On average, although both plots are irrigated by water from collectively owned wells, the plot in a connected village uses 52% ( $\exp^{0.419} - 1$ ) more water than the plot in an isolated village (column 4, row 1). The difference is measured in percentages of the rate of pumping on the base group plots and is statistically significant. This result supports Hypothesis 1a, that the connectedness of a village will increase the rate of pumping when other factors are held constant. The result also supports Hypothesis 1b, but the evidence is not as strong. The magnitude of the coefficient on the interaction term, Private-Connected, is larger than that on the interaction term, Private-Isolated by 0.23 (column 4, row 2 and 3). This result shows that on average, although both plots are irrigated by water from privately owned wells, the plot in a connected village uses 26% more water than the plot in an isolated village. The percentage difference, however, is smaller than under collective management and is not statistically significant. The percentage difference is smaller under private well management, probably because the effect of the connectedness of a village on the private cost is much lower than the effect on the social cost. In other words, if a household ignores the externality of his pumping on other households with the same village, the connectedness of aquifers will have small *additional* impact on his pumping.

There is also evidence that supports Hypotheses 2a and 2b. In isolated villages, the rate of pumping on a Collective-Isolated plot is reduced by 42% ( $\exp^{-0.544} - 1$ ) from the level on a Private-Isolated plot (table 4, column 4, row 3 and 4), and the difference is statistically significant. The coefficient on Collective-Connected is also smaller than the coefficient on Private-Connected by 0.356. The rate of pumping on a Collective-Connected plot is reduced by 30% ( $\exp^{-0.356} - 1$ ) from the level on a Private-Connected plot. So there is some evidence that when village leaders are in charge, as in the case of collective well management, leaders are likely to allocate groundwater among households in a way that takes into account the welfare of all villagers, and which considers the long run use of the resource.

Even though groundwater markets in rural China are not monopolistic,<sup>14</sup> in order to examine whether there are other differences that

<sup>13</sup> Mu is the metric unit of land area that is used in China. 1 mu = 1/15 hectare.

<sup>14</sup> Zhang et al. (2008) used the village-level data from the CWIM Survey and concluded that groundwater markets in rural China are not monopolistic based on the following empirical evidence. First,

may affect our results, we have separated the private well ownership variable into two variables: one for well-owning households (Own Well) and another for water-buying households (Buy Water). These variables are then interacted with the variable measuring the connectedness of the aquifer to create two interaction dummies: Private (Own Well)-Connected and Private (Buy Water)-Connected. Since only 3 plots are located in isolated villages and irrigated using water from own wells, we did not separate the variable Private-Isolated into Private (Own Well)-Isolated and Private (Buy Water)-Isolated. Table 5 reports these alternative specifications. Using results from all four specifications in table 5, we fail to reject the null hypothesis that the coefficient on the variable Private (Buy Water)-Connected equals the coefficient on the variable Private (Own Well)-Connected. For example, the  $p$ -values are 0.155 and 0.434 using the first two specifications. Thus, results from table 5 did not indicate any difference in terms of water use between the well-owning households and water-buying households that are statistically significant.

## Conclusions

In this paper we show empirically that whether the community-based management of groundwater resources is adequate for resource conservation depends crucially on the nature of the aquifer; that is, whether or not the aquifer underlying a village is connected to or

isolated from the aquifers underlying neighboring villages. The administrative boundary of a village often does not match with that of the aquifer. Our results show that when such mismatches exist, the incentives of villages to conserve water are undermined. Specifically, when a village's aquifer is connected to those of neighboring villages, the rate of pumping increases significantly even under collective well management. Our results suggest that when a village is not hydrologically isolated, the success of community-based management would depend on cooperation within the village as well as cooperation among villages that share the connected aquifers. Therefore, future research should also focus on studying the factors that can lead to cooperation among villages. For example, intervention by upper-level government may be required. Alternative institutions, such as water user associations set up along the hydrological boundaries of the aquifer, may be more effective in managing water. This implication can be generalized to the management of other resources since the mismatch between administrative boundary and natural resource boundary is also common for other types of CPRs, for example in the case of woodlands (Campbell et al. 2001).

Our analysis also indicates the importance of bringing hydrology into water resource management. In many developing countries including China, no hydrologists are involved in managing groundwater. Because of the lack of hydrology information at the village level, we have partly relied on the perception of village leaders regarding the connectedness of aquifers. Although the use of perceptions is appropriate when studying the behavior of water users, it is important and essential that policy-makers should make their decisions based only on accurate information on the hydrological structure of aquifers. Further research should also focus on the benefit of providing hydrology information in groundwater management.

Finally, when studying community-based management, it is also important to pay attention to the different institutional arrangements at the village level. Our results show that collective well management and private well management may have generated different resource outcomes. This point is also important in the management of other types of CPRs. For example, Sakurai et al. (2004) compared the collective management and individual management of Nepal's village forestry and also found significant differences.

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the markup ratio is, on average, 1.2. This ratio, although high, is within with the range of ratios that groundwater markets in South Asia countries have been interpreted as being competitive (Fujita and Hossain 1995 and Palmer-Jones 2001). The high ratio mostly reflects water sellers' risk premium. Second, the profits from selling water (including the fixed and variable costs in pumping and selling water) are generally small, even when the value of family labor is not accounted for. Third, the variation in the price of water is mainly due to regional differences among villages, not from within villages. Since groundwater markets are localized and most transactions are among farmers in the same villages, if markets are competitive, we would expect most price variation to come from between villages, not from within villages. Finally, one possible reason for not observing the market power of well-owning households is the wide adoption of surface plastic pipe (or hoses, called "little white dragon" in rural China), which is cheap but greatly enhances conveyance efficiency. More than 70% of well owners used surface pipes to deliver water. This reduces the probability that a well-owning household can exert monopoly power because buyers might switch to the next closest well if the price difference is less than the extra conveyance cost. Therefore, in the sense of water users, the only difference between the two types of households is the price of water they pay (the price of water is higher for water buyers than the cost of water for those with their own well), which is controlled for in our analysis.

**Table 5. The Effect of Well Ownership and Connectedness of Aquifers on the Rate of Pumping**

Base group:	Dependent Variable: Log of the Volume of Water Pumped per mu, m <sup>3</sup> /mu							
	Use Interview-based Measure of Connectedness				Use Hydrology-based Measure of Connectedness			
	(1) OLS		(2) IV/GMM <sup>a</sup>		(3) OLS		(4) IV/GMM <sup>a</sup>	
Collective-Isolated								
Collective-Connected	0.250***	(0.0714)	0.374*	(0.189)	0.234**	(0.105)	0.426**	(0.153)
Private (Own Well)-Connected	0.307***	(0.0946)	0.877***	(0.290)	0.294**	(0.124)	0.867**	(0.305)
Private (Buy Water)-Connected	0.385***	(0.0793)	0.682***	(0.179)	0.379***	(0.115)	0.762***	(0.173)
Private-Isolated	0.219***	(0.0617)	0.736***	(0.226)	0.219***	(0.0764)	0.594**	(0.245)
Water cost, log	-0.174***	(0.0360)	-0.178***	(0.0362)	-0.186***	(0.0390)	-0.184***	(0.0374)
<i>N</i>	-0.000473	(0.000676)	-0.000889	(0.000988)	-0.000671	(0.000640)	-0.000580	(0.000942)
Well density	-1.717	(1.229)	-4.002	(2.263)	-1.146	(1.305)	-3.690	(2.405)
Amount SW	-0.0000467	(0.000191)	-0.0000393	(0.000185)	-0.000130	(0.000210)	-0.0000646	(0.000205)
Num Lack	-0.0330*	(0.0180)	-0.0128	(0.0220)	-0.0369	(0.0245)	-0.0402	(0.0336)
Crop price, log	-0.251	(0.548)	-0.747	(0.731)	-0.315	(0.513)	-0.601	(0.664)
Fertilizer price, log	-0.0436	(0.0496)	0.0176	(0.0682)	-0.0445	(0.0509)	0.0124	(0.0589)
Drought-tolerant	-0.0889***	(0.0313)	-0.115**	(0.0442)	-0.0890**	(0.0341)	-0.0978**	(0.0450)
Sand	0.0371	(0.0306)	0.0549	(0.0601)	0.0288	(0.0315)	0.0265	(0.0557)
Plot size, log	-0.0517**	(0.0222)	-0.0761**	(0.0258)	-0.0413*	(0.0217)	-0.0600*	(0.0302)
Distance	0.0000708	(0.0000912)	0.000199	(0.000151)	0.00000337	(0.000101)	0.0000498	(0.000118)
Lined	0.000567	(0.000564)	0.000518	(0.000787)	0.000523	(0.000609)	0.000622	(0.000712)
Irrigation method	0.0426	(0.0434)	0.0200	(0.0382)	0.0495	(0.0403)	0.0319	(0.0343)
Age	-0.000928	(0.00192)	-0.000161	(0.00296)	-0.00124	(0.00214)	-0.00115	(0.00317)
Education	-0.00154	(0.00776)	0.00656	(0.0133)	-0.00350	(0.00881)	0.00624	(0.0125)
Hired labor	-0.000846	(0.00140)	-0.00236	(0.00146)	-0.000210	(0.00147)	-0.00111	(0.00146)
Constant	5.573***	(0.241)	5.637***	(0.448)	5.589***	(0.246)	5.580***	(0.417)
County fixed effects	Yes		Yes		Yes		Yes	
Number of observations	196		196		196		196	
Adjusted R <sup>2</sup>	0.460		0.067		0.433		0.192	

Standard errors in parentheses (clustered at the village level); \*, \*\*, \*\*\* significant at the 10%, 5% and 1% levels, respectively.

<sup>a</sup>Five variables are used to instrument for well ownership: a dummy variable that equals one if there were policy efforts by upper level government to encourage private wells (e.g. whether the upper level government organized meetings or issued directives, whether the government provided fiscal subsidies for investment in wells); household asset per capita; household land per capita; the share of groundwater irrigated area in the household in 2001; and whether land was reallocated between 2002 and 2004.

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**Appendix Table 1. Summary Statistics**

	Mean	sd	Min	Max
Log of the volume of water pumped per mu, m <sup>3</sup> /mu	6.11	0.29	5.53	6.97
Water cost	0.16	0.14	0.012	0.71
<i>N</i>	38.28	41.47	3	173
Well density	0.027	0.030	0.002	0.115
Amount SW	24	103	0	1018
Num Lack	0.95	0.93	0	3
Crop price, log	0.39	0.48	0.15	0.47
Fertilizer price, log	-0.39	0.48	-1.64	0.26
Drought-tolerant	0.29	0.46	0	1
Sand	0.24	0.43	0	1
Plot size, log	0.56	0.86	-2.30	2.16
Distance	136.6	205.2	0	1000
Lined	57.22	48.96	0	100
Irrigation method	0.214	0.411	0	1
Age	40.43	10.27	21	78
Education	5.63	2.36	0.5	13.5
Hired labor	5.08	10.50	0.00	85.91

**Appendix Table 2. Crop Mix, Nature of the Aquifer and Type of Well Management**

	Use Interview-based Measure of Connectedness		Use Hydrology-based Measure of Connectedness		Collective	Private
	Isolated	Connected	Isolated	Connected		
Percentage of sown area in wheat (this also includes a small percentage of other grains, beans, and legume grown in the winter season)	43	44.8	45.3	44.1	46.9	42.5
Percentage of sown area in corn (this also includes a small percentage of other grains, beans and legumes grown in the summer season)	38.1	29.2	33.1	31.4	31.5	31.8
Percentage of sown area in rice (rice is only grown in Henan Province and only in the winter season)	7.5	6.5	9.6	6.2	4.3	8.5
Percentage of sown area in cotton and other cash crops such as oil crop, fruits and vegetables and trees (most cash crops are grown in the summer season)	11.5	19.4	11.9	18.4	17.2	17.2

*Note:* The winter season starts in the previous October when crops are planted and ends in June when crops are harvested. The summer season starts in June when crops are planted and ends in October when crops are harvested.