The Effects of Well Management and the Nature of the Aquifer on Groundwater Resources

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Abstract

This paper examines how the nature of a resource affects the effectiveness of community-based management on resource conservation. We focus on groundwater management in rural China because there are different types of community-based groundwater management in different communities. In some communities wells are collectively owned and the community leader allocates water among households. In our paper we call this collective well management. In other communities wells are privately owned and households make their own pumping decisions. We call this private well management. In comparing the effects of different types of well management on the groundwater resource, unlike previous studies, we control for the nature of the aquifer. Communities are divided into two additional groups based on the nature of the aquifer: connected communities whose aquifers are connected to neighboring communities due to lateral groundwater flows; and isolated communities that are hydrologically isolated. Results indicate that whether community-based management is adequate for resource conservation depends crucially on the nature of the aquifer. Empirical analysis using a unique set of household level data shows that households located in isolated communities use less water than households in connected communities, controlling for the type of well management. Furthermore, results show that in isolated communities households under collective well management use 20% less water than households under private well management. In connected communities, however, no difference in water use is observed between collective well management and private well management.

Keywords: community-based management; connected community; isolated community; collective well management; private well management

JEL codes: Q15; Q25; O17

The Effects of Well Management and the Nature of the Aquifer on Groundwater Resources

The management of local common property resources (CPR) is among the most important issues in the study of the development of rural areas and resource conservation in developing countries. Failures of centralized management by governments have made decentralized and community-based conservation initiatives an attractive alternative to the management of the CPR. The underlying assumption is that since local communities possess time- and place-specific knowledge (e.g., Ostrom, 1990), they are better managers of natural resources than outside agents. Some also think that since communities have a long-term need for the renewable resources near where they live, they have the incentive to manage their natural resources in a sustainable way. International funding agencies, such as the World Bank, have directed large sums of money and a lot of effort toward community-based conservation and resource management programs and policies. 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 transferred control of the resource to local communities (Vermillion, 1997).

Research on community-based resource management in developing countries has been growing rapidly in the past two decades (e.g., Agrawal and Gibson, 1999; Baland and Platteau, 1996; Western and Wright, 1994). Most research has focused on assessing the performance of community 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; Poteete and Ostrom, 2004) and wealth inequalities (Baland and Platteau, 1999; 1998).

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 communities 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 et al. (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 in studying the management of groundwater resources, a typical CPR. Brozović et al. (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 flow laterally across the aquifer easily.[1] 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 rate of pumping by a farmer depends on the speed of lateral flows between his well and the wells of neighbors, which is a function of the transmissivity of the aquifer.

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[1] 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).

This study has two goals. The first goal is to examine the effectiveness of community-based management of groundwater resources on resource conservation when accounting for the nature of the aquifer. The second goal 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. Although China's water law stipulates that groundwater resources in aquifers belong to the state, in rural areas communities that lie above the aquifers have the de facto rights to the groundwater.[2] Access to groundwater in an aquifer is restricted by membership of communities that lie above the aquifer and often associated with the ownership of wells.[3] Without effective regulation by the national or sub-national government, communities are in charge of managing groundwater resources. Furthermore, institutional arrangements within the communities define the rules of groundwater governance and, in particular, water allocation rules. However, specific institutional arrangements differ among communities. In some rural communities wells are collectively owned and groundwater is managed by the community leader. Households manage their own plots but rely on the groundwater that is pumped and delivered by the community leader. We call this type of community-based groundwater management *collective well management*. In other rural communities, wells are owned by private individuals

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[2] 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 build up a regulatory framework has been weak. At the national level, there is not one water regulation that specifically focuses on groundwater management issues (Wang et al., 2009).

Outside of the central government, sub-national governments, provincial, prefectural, and county water resources bureaus are in charge of managing groundwater (Foster et al., 2004; Lohmar et al., 2003). In order to manage the de facto allocation of the nation's groundwater, there have been policies promulgated to control the right to drill wells, manage the spacing of wells and regulation of the fees for the collection of water resources. However, there has been little success in the implementation of these policy measures on groundwater management (Wang, et al., 2009). According to the Northern China Water Resources Survey data the authors collected in six provinces in northern China (Wang, et al., 2009), less than 10% of well owners obtained a well drilling permit before drilling, despite the nearly universal regulation requiring a permit. Only 5% of the community leaders believed that well drilling decisions required consideration of well spacing. Even more noticeable is the fact that water extraction charges were not imposed in any community and there were no quantity limits put on well owners. Indeed, in most communities in China, groundwater resources are almost completely unregulated by the national government or sub-national governments.

[3] Unlike the case of the US, the de facto rights in rural China are not associated with land ownership or historic use.

and well owners make management decision independent of each other. We call this type of management *private well management*. Depending on the institutional arrangement, different actors are in charge of managing water and different rules of governance are applied in different communities. Therefore, the effectiveness of community-based management may be different under different institutional arrangements. In this study, we compare the effects of different types of well management (in our case, collective well management versus private well management) on groundwater resource conservation. Importantly, when we seek to measure the effect of different well management on conservation, we will take into account the nature of the aquifer.

The contribution of this paper is two-fold. First, this paper is one of the few studies that *empirically test* the effectiveness of the community-based management on resource conservation. Despite the extensive literature on CPRs, most studies are either based on only case studies ("small-N studies") or theoretical formulations (Poteete and Ostrom, 2008). Our study uses a set of survey data and uses econometric analysis to examine the questions of interest. Second, this study also 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 et al. (2006) and Saak and Peterson (2007) have made significant contributions to the theory side of the economics of groundwater; their work, however, contains no empirical evidence.[4] Even fewer studies have linked the nature of the aquifer to community-based groundwater management.

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[4] 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 for approximating the value function, which measures the net present value of groundwater, when numerically solving a dynamic programming problem. Again, neither study contains empirical evidence.

The rest of the paper is organized as follows. First, we describe the basics of China's well management and the nature of groundwater aquifers in northern China. Next, we develop the hypotheses that we use to test the effectiveness of community-based groundwater management. In the fourth section we describe the survey data that are used in the empirical analyses of the study. In the fifth section we present the empirical framework. In the sixth section we report and discuss the estimation results and in the final section we summarize and draw conclusions.

Well management and the nature of the aquifer 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^3 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 played an increasingly important role in the region's economic growth. In 2007, on average, 37% of the total water supply (industrial, residential and agricultural sectors) comes from groundwater (Ministry of Water Resources, 2008). Agriculture relies even more heavily on groundwater. In northern China, 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).

The rapidly growing industrial sector and an increasingly wealthy urban population, however, are beginning to compete with the agricultural sector for water. As a result, groundwater resources are diminishing in large areas of northern China. For example, between 1958 and 1998 groundwater levels in the Hai River Basin (HRB), one of the main economic and political centers of China, fell by up to 50 meters in some of its shallow aquifers and by more than 95 meters in some of its deep aquifers (Ministry of Water Resources et al., 2001).

As groundwater resources have become scarcer, there also has been a simultaneous transition of ownership of wells in northern China. Before the rural reforms in the 1980s, the wells in almost all rural communities were collectively owned. As the curator of collective assets, the community leader made decisions 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 community leader often hires a well operator to pump water and deliver to households under his instruction.

With falling groundwater levels and changes in policies that weakened the collective's 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 et al., 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 communities (Wang, et al., 2007). By 2004, the share of privately owned wells rose sharply to 70%, shifting the decision-making of groundwater management largely into the hands of private individuals.

The changes in well management have the potential for affecting the nation's water resources. The characteristics of China's rural communities mean that when community leaders are in charge (as in the case of collective well management), leaders are likely to allocate groundwater among households in a way that is socially optimal. First, partly because their re-election or political promotion depends on the satisfaction of at least the majority of households within the community (Luo et al., 2007), community leaders would not only think in terms of the benefit that the whole community (instead of any individual household) could obtain from using groundwater but also seek to maximize the net present value of benefits from all time periods (instead of just benefit from the current period).[5] Second, the equal distribution of the most important production factor, land, makes it easier to for the community leaders to allocate water among households. Unlike other countries such as India, land is relatively equally allocated among households in rural China both in terms of land size (per household) and soil quality. The egalitarian nature of land distribution not only helps avoid the potential distortions and inefficient outcomes that could result from regulation (in our case, the community leaders makes the decisions on how much water to allocate to each household) under high inequality, it also reduces the cost of regulation and the potential for conflict (Baland and Platteau, 1997; 1998). In short, when community leaders are in charge of managing groundwater, they may want to behave more like a social planner (as opposed to an individual well owner) and have an incentive to internalize the externalities associated with pumping and conserve groundwater for future uses 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 or buy water from other households that own wells. In either case, households make their own pumping decisions and each household would be expected to only seek to maximize its private benefits (Bromley, 1982). Since there is not a social-planner-like manager, such as the community leader, households almost certainly would ignore the externalities that their pumping imposes on other households that are pumping (or using water) from the same aquifer. The incentive of a private household to conserve water for future use also

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[5] Similarly, Bromley and Chapagain (1984) treat south Asian communities as the decision-making units, where, the community as a whole, has “private” control of resource use.

diminishes rapidly as the number of households increases. Communities in our sample areas are characterized by large numbers of households. The average number of households per community is 387. As a result, under private well management, pumpings by individual households is likely to result in a "tragedy of the commons."

Partly because the shift to private well management during 1990s coincided with the rapid decline of water levels in aquifers, scholars have blamed private well management for the emerging groundwater crisis in northern China (Zhang and Zhao, 2003). Indeed, if collective well management produced sustainable extraction while the private well management resulted in the tragedy of the common, 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 northern China's groundwater resources. If this were the case, then those that are concerned with conserving groundwater resources should prefer (or at least consider) collective well management as the way to manage groundwater resources. However, facts show that there may be inconsistencies in the argument that the private well management unambiguously leads to the depletion of groundwater resources. In one of the few studies on this subject, Wang et al. (2005) show empirically that groundwater levels in communities were not lower in the communities in which wells were managed by private owners. Their empirical evidence suggests that private well management is at least as effective as collective well management in managing groundwater resources.

When trying to explain why there is little difference between collective well management and private well management in terms of their effects on groundwater resource conservation, we believe the nature of 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 communities were “stealing” groundwater *from his community*. He believed that groundwater was flowing laterally from the aquifer under his own community into the command area of a well that his neighbors had sunk near the border of the two communities. The leader also told us that he would have sunk a new well of his own to compete with his neighbors in extracting groundwater, had his community had enough capital to do so.

Such anecdotes are not uncommon. The stories clearly indicate the nature of the aquifer may be affecting the behavior of community leaders. If water in an aquifer is accessible not only to the community above the aquifer but also to neighboring communities (probably due to low storativity and high transmissivity — Brozović, et al., 2006), the water level in one community may be affected by the pumping of neighboring communities and vice versa. If this were the case, we could say that the aquifers underlying different communities are *connected* and thus the water level in a community and the pumping of his neighboring communities are correlated. When recognizing this correlation, the community leader would probably stop acting like a social planner-like manager and begin to compete with other communities in extracting groundwater. Hence, it is possible that connectedness of communities—even when the wells are managed by community leaders—can lead to inefficient use of groundwater resources.[6] In other words, even under collective management, when aquifers underlying different communities are connected, collective well management may also result in non-cooperative extraction among different communities. If this were so, it may explain the results of Wang et al (2005) — that there was

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[6] Negri (1989) also shows theoretically that a water user (a community in our case) may extract more than what he/she would have had there been no competition among users to discourage the extraction of other users. This strategic behavior will exacerbate the inefficient extraction of groundwater resources in the case when the aquifers underlying different communities are connected.

little (if any) difference in the rate of the drawdown of the groundwater between communities under collective well management and communities under private well management.

Conceptual Basis and Hypotheses

The previous section presents a puzzle: the characteristics of China's rural communities indicate that collective well management would be more effective in conserving groundwater than private well management while the (limited) empirical evidence indicates that there is little difference between them. In this section we first construct four game theoretical models that characterize the behavior of community leaders and households under different types of well management when communities are drawing groundwater from different types of aquifers. Based on the behavioral differences that are derived from the output of the models, we then develop a set of hypotheses that may explain the puzzle. In the following sections we will then use a set of household level data to test these hypotheses.

Four models

In the rest of the paper, we will call a community whose aquifer is connected to those of neighboring communities a *connected community* and a community that is hydrologically isolated from other communities an *isolated community*. Isolated communities and connected communities are illustrated in Figure 2 of Appendix 1. In this section we assume that there is only one well in the community and it is used by N households. All N households are assumed to be identical. The periodic benefit of a household from pumping w_t unit of water at time t net of the cost of other inputs is $B(w_t)$, which is concave in w_t. Inputs other than water are assumed to be optimized conditional on the level of w_t. The unit cost of pumping water, $C(S_t)$, is such that $\partial C(S_t)/\partial S_t < 0$.

Model 1. Collective well management in an isolated community

Under collective well management, the community leader maximizes total benefits of utilizing groundwater from current period as well as considering payoffs from future periods. Let $V_t(S_t)$ be the value function of each household, which is the net present value of the returns from water over all future periods when the current level of the stock of groundwater in the aquifer is S_t. In the form of the Bellman equation, the problem of the leader of an isolated community can then be written as:

$$\begin{aligned} &NV_t(S_t) = \underset{w_t}{\text{Max}}\ N\left\{B(w_t) - C(S_t)w_t + \delta V_{t+1}(S_{t+1})\right\} \\ &s.t. \quad S_{t+1} = S_t - Nw_t + R \end{aligned} \tag{1}$$

where S_{t+1} is the level of the groundwater stock at time $t+1$, Nw_t is the total volume of pumping of the community and R is the level of natural recharge. The parameter, δ, is the discount factor associated with the future payoffs, $V_{t+1}(S_{t+1})$. Note, since an isolated community is hydrologically isolated from other communities, S_{t+1} is not affected by the pumping of neighboring communities. Differentiating (1) with respect to w_t gives the decision rule that the leader will follow to determine how much water to allocate to each household:

$$\partial B(w_t)/\partial w_t - C(S_t) = \delta\, N\partial V_{t+1}(S_{t+1})\big/\partial S_{t+1} \tag{2}$$

Model 2. Collective well management in a connected community

In a connected community, S_{t+1} is affected by the pumping of neighboring communities. For convenience, suppose there are only two communities whose aquifers are connected and suppose that the stocks of groundwater for the two communities are the same at period *t*. That is, $S_t^1 = S_t^2 = S_t$, where the superscripts are indices for communities and subscripts denote time periods. Since wells in different communities are not located within a close distance to each other and groundwater usually flows slowly across space (which is the case in some of our study areas in the HRB, Chen, 1999), within the irrigation season, each community extracts groundwater independently of each other. However, between period *t* and period *t* + 1, groundwater will flow laterally towards the community with the higher level of aggregate pumping in period *t*. Using Darcy's law, the inter-period lateral flow from community 2 to community 1 is given by:[7]

$$-\alpha[(S_t^1 - Nw_t) - (S_t^2 - W_t^{2*})] = \alpha[Nw_t - W_t^{2*}] \tag{3}$$

where W_t^{2*} is the aggregate pumping in community 2. An asterisk is added to denote the fact that community 1 cannot control the pumping of community 2 and so has to take it as given. The parameter α summarizes the hydraulic property of the aquifers and is a function of the hydraulic conductivity (which measures the ease with which water can move through the aquifer) and the distance between the two communities. The larger is α, the more connected are the two communities.[8] In short, the parameter α can be thought of as a measure of the degree of connectedness of the two communities. We will focus on community 1 and suppress the superscript 1 in the following analysis. Similar to Negri (1989), Dixon (1991) and Provencher and Burt (1993), a feedback Nash game is used. The leader in community 1 is involved in the following difference game with other communities:

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[7] The set up used here is similar to the set up used in Saak and Peterson (2007).

[8] The value of α is bounded above by 0.5 since an α of 0.5 corresponds to the case that the water stock in the two communities are equalized in period t+1 (and thus no further lateral flow).

$$
\begin{aligned}
&N\tilde{V}_t(S_t) = \underset{w_t}{\mathrm{Max}}\ N\left\{B(w_t) - C(S_t)w_t + \delta\tilde{V}_{t+1}(S_{t+1})\right\} \\
&s.t. \quad S_{t+1} = S_t - Nw_t + \alpha[Nw_t - W_t^{2*}] + R
\end{aligned}
\tag{4}
$$

where $\tilde{V}_t(S_t)$ is the value function of each household in a connected community under collective well management. Note that when α takes the value of zero, problem (4) reduces to the case of an isolated community, that is, the case being analyzed in model (1). The decision rule (or the best response function of community 1) for problem (4) can be expressed as:

$$
\partial B(w_t)/\partial w_t - C(S_t) = \delta N(1-\alpha)\partial\tilde{V}_{t+1}(S_{t+1})\big/\partial S_{t+1} \tag{5}
$$

Model 3. Private well management in an isolated community

Under collective well management (Model 1 and Model 2), the community leader is in charge of allocating water among households. In contrast, under private well ownership, households use water from a well that is privately owned and managed; each household makes its own decision on how much to pump. In an isolated community, each household is solving the following problem to maximize his own value function:

$$
\begin{aligned}
&\widehat{V}_t(S_t) = \underset{w_t}{\mathrm{Max}}\ \left\{B(w_t) - C(S_t)w_t + \delta\widehat{V}_{t+1}(S_{t+1})\right\} \\
&s.t. \quad S_{t+1} = S_t - w_t - (N-1)w_t^* + R
\end{aligned}
\tag{6}
$$

where $\widehat{V}_t(S_t)$ is the value function of a household in an isolated community and w_t^* is the pumping of other households in the community. The household extracts water according to the decision rule:

$$
\partial B(w_t)/\partial w_t - C(S_t) = \delta\,\partial\widehat{V}_{t+1}(S_{t+1})\big/\partial S_{t+1} \tag{7}
$$

Model 4. Private well management in a connected community

In a connected community, each household under private well management still only maximizes his own value function but the groundwater stock he faces is now affected by the pumping of neighboring communities:

$$\begin{aligned} &\breve{V}_t(S_t) = \operatorname*{Max}_{w_t} \ \left\{ B(w_t) - C(S_t)w_t + \delta \breve{V}_{t+1}(S_{t+1}) \right\} \\ &s.t. \quad S_{t+1} = S_t - w_t - (N-1)w_t^* + \alpha[w_t + (N-1)w_t^* - W_t^{2*}] + R \end{aligned} \tag{8}$$

where $\breve{V}_t(S_t)$ is the value function of a household in a connected community. The household extracts water according to the decision rule:

$$\partial B(w_t)/\partial w_t - C(S_t) = \delta(1-\alpha)\partial \breve{V}_{t+1}(S_{t+1}) \big/ \partial S_{t+1} \tag{9}$$

Testable hypotheses

The decision rules developed in equations (2) and (5) clearly show that depending on whether a community is isolated or connected, the rate of pumping under collective well management can differ. Both equations (2) and (5) state that the community leader balances the net marginal benefit of pumping one more unit of water at time *t*, the Left-Hand Side (LHS) of the equation, with its marginal cost — the present value of one more unit of water available in the future periods, the Right-Hand Side (RHS) of the equation. Comparing the RHS of equation (2) and equation (5) shows that the value of water to the community leader in a connected community is discounted by the factor of $1-\alpha$, relative to the leader in an isolated community (when $\alpha = 0$). This is because the leader in the connected community knows that if his community leaves one more unit of water in the aquifer at time *t*, he will likely lose α unit to community 2 between *t* and *t*+1 through the lateral flow between two aquifers. As a consequence, he values the water less (by a factor of α). Because of this lower valuation of water, the leader will allocate more water among households when the community is connected than when the community is isolated.

Intuitively, this result can be explained as follows: The LHS of both equation (2) and (5) are $\partial B(w_t)/\partial w_t - C(S_t)$; since $B(w_t)$ is concave in w_t, at any given level of S_t and N, the smaller is the RHS (that is, the lower is the value of water), the higher is the level of w_t. A more detailed analytical proof of this result is provided in Appendix 2. We summarize the above result in the following hypothesis:

> **Hypothesis 1a**: Suppose one household is in an *isolated* community and another household is in a *connected* community. Both households use groundwater allocated by the community leader in a community that is under *collective* well management. Further suppose that the two communities have the same level of groundwater stock and the same number of households. Under such a set of assumptions, the household in the connected community will be allocated more water than the household in the isolated community.

Similar results to that in Hypothesis 1a can be derived for households in a community that is under private well management by comparing equations (7) and equation (9). We summarize it in the following hypothesis:

> **Hypothesis 1b**: Suppose one household is in an *isolated* community and another household is in a *connected* community. Both households decide how much groundwater to obtain from *privately* owned and managed wells. Further suppose that the two communities have the same level of groundwater stock and the same number of households. Under such a set of assumptions, the household in the connected community will use more water than the household in the isolated community.

If hypothesis 1a and 1b are true, when we compare the effectiveness of collective well management and private well management in resource conservation, it is important to take into account whether or not the communities under comparison are isolated or connected. To control for the nature of the aquifer, when we compare the effectiveness of the different types of well management, we only do the comparison among isolated communities or only among connected communities. We first start with the comparison among isolated communities. Using the decision rules in equation (2) and (7), we can show that collective well management leads to water conservation in isolated communities. Equation (7) states that a household in an isolated community, when under private well management, only considers his own private cost, $\delta \partial \widehat{V}_{t+1}(S_{t+1}) / \partial S_{t+1}$, when he balances the marginal benefit and marginal cost of pumping. In contrast, equation (2) states that if the same household were in a community that is under collective well management, the community leader, when deciding how much water to allocate to the household, will consider the social cost of the pumping of the household, $\delta N \partial V_{t+1}(S_{t+1}) / \partial S_{t+1}$. That is, the community leader will internalize the externality the household imposes on the other $N - 1$ households in the community. Since the household under private well management faces lower marginal cost than the household under collective management, the level of w_t of the household under private well management will be higher than that of the household under collective management.[9] Following this logic, we develop the following hypothesis:

> **Hypothesis 2a**: Suppose one household is in under private well management and another household is under collective management. Both households are located in isolated communities. Further suppose the two communities have the same level of groundwater stock and the same number of households. 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.

Similar results to that in Hypothesis 2a can also be derived for households in connected communities by comparing equation (5) and equation (9). We summarize it in the following hypothesis:

> **Hypothesis 2b**: Suppose one household is in a community under private well management and another household is in a community under collective management. Both households are located in connected communities. Further suppose the two communities have the same level of groundwater stock and the same number of households. Then the volume of water pumped by the household in the community under private well management will be higher than the volume of water allocated to the household in a community under collective well management.

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[9] This result has been formally proved in many previous studies. A detailed proof is presented in Provencher and Burt (1993: 144-146).

We also can show that collective well management is more effective in conserving water resources in isolated communities than in connected communities. In an isolated community, a household under collective well management would pay $\delta(N-1)\partial V_{t+1}(S_{t+1})/\partial S_{t+1}$ in addition to his own private cost (equation 2). At a given level of S_t and N, the larger is the term $\delta(N-1)\partial V_{t+1}(S_{t+1})/\partial S_{t+1}$, the more a community leader would need to reduce the water allocated to a household relative to the case when the household were in a community under private well management. That is, more water is conserved. This term is the reason that collective well management leads to resource conservation. Let's call it *the conservation term*. In a connected community, a household in a community under collective well management would pay $\delta(N-1)(1-\alpha)\partial\tilde{V}_{t+1}(S_{t+1})/\partial S_{t+1}$ in addition to his own private cost (equation 5). We can show that the magnitude of the conservation term is smaller in a connected community. First of all, the conservation term in a connected community is discounted by a factor of $1-\alpha$ relative to that in an isolated community. Furthermore, in a connected community, the marginal value of one more unit of groundwater stock, $\partial\tilde{V}_{t+1}(S_{t+1})/\partial S_{t+1}$, is also smaller than the counterpart in an isolated community, $\partial V_{t+1}(S_{t+1})/\partial S_{t+1}$ (an analytical proof is provided in Appendix 3). Intuitively, one more unit of water left in the groundwater for future use has a lower value in a connected community because the community may lose part of it to neighboring communities through lateral flows. Because the magnitude of the conservation term is smaller in a connected community, a leader will not be able conserve as much water as in an isolated community. Following this logic, we develop the following hypothesis:

> **Hypothesis 3**: When we define water conservation as the difference between the rate of water use in communities under collective well management and the rate of water use in communities under private well management, more water can be conserved in an isolated community than in a connected community, given the level of groundwater stock and the number of households.

Hypothesis 2a, Hypothesis 2b and Hypothesis 3 are developed taking into account whether a community is isolated or connected. However, in Wang et al. (2005) or other studies, all communities (either connected or isolated) under private well management are compared to all communities (either connected or isolated) under collective well management. In such a comparison, the effects of different types of well management on the rate of pumping are not separated from the effects of the nature of the aquifer (connected or isolated) on the rate of pumping. This may have caused some bias in the results of comparison.

This bias can be clearly seen using an extreme case. Suppose in a region privately owned wells are only located in isolated communities and collectively owned wells are only in connected communities. In such a case, community leaders are allocating water among households under collective well management according to equation (5) while households under private well management are pumping according to equation (7). On the one hand, community leaders who are in communities with collective wells are taking into account the social costs of pumping (captured by N on the RHS of equation 5) and thus will allocate less water to a household than the level the household would pump itself if it is in a community that is under private well management. On the other hand, the connectedness of communities undermines the incentive of community leaders to conserve water (the RHS of equation 5 is discounted by $1-\alpha$). In this case, the failure to account for the nature of the aquifer will result in under-estimation of the potential of collective well management in resource conservation. This is because the conservation efforts are partly offset by the incentive to over-pump in competition with neighboring communities. If N is small and α is large, the RHS of (5) may even be lower than that of (7) and a household under collective well management may be observed to use more water than a household under private well management.[10]

This case shows that if the nature of the aquifer is ignored, the comparison of water use by households in communities under collective well management and those in communities under private well management may lead the analyst to the wrong conclusion. The failure to account for the nature of the aquifer may explain the puzzle that the characteristics of China's rural communities indicate that collective well management has the potential to conserve water while the empirical evidence shows otherwise. Following this logic, we develop the following hypothesis:

> **Hypothesis 4**: Suppose some communities in a region are connected while others are isolated. Then the comparison between the effects of collective well management and private well management on the rate of water use of households without controlling for the effects of the nature of the aquifer may result in bias.

Data Description

The data used in the study come from the 2004 China Water Institutions and Management (CWIM) Survey. The data 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. Henan province is located in the middle reaches of the Yellow River Basin. These two river basins are two of the nine major river basins in China. In Hebei province three counties were randomly selected according to their locations, which were correlated with the extent of water scarcity in the HRB. Xian County is located along the coastal belt, the most water scarce area of China; Tang County is located along the inland belt, an area with relatively

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[10] We can also show that comparing a household under collective well ownership in an isolated community to a household under private well ownership in a connected community results in overestimation of the potential of collective well ownership in resource conservation.

abundant water resources since it is next to the mountains in the eastern part of Hebei province; and Ci County is located in the region between the coast and mountains. In Henan counties were randomly selected from irrigation districts with varying distances from the Yellow River. Locations further away from the river are typically associated with increasing water scarcity. Appendix 3 describes the location and the general hydrogeological structure of the study area.

After the sample counties were selected, we randomly selected 48 communities. According to our data, there are five communities that only used surface water for irrigation in 2004. In the remaining 43 communities, on average, 87% of the irrigation water came from groundwater. In the rest of the paper we will focus these groundwater-using communities. In the CWIM survey enumerators interviewed three sets of respondents: community leaders, randomly-selected households (between one to four households per community) 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 and 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: fertilizer, labor (by production activity), machinery (use of own equipment or rent), pesticide, plastic sheeting and other inputs.

In our empirical analysis plot is used as the unit of analysis. Since wheat is the major crop 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).

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 communities under collective well management this is the amount of water that the community leader allocated to each household. In the communities 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 communities households 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 he/she obtained groundwater for irrigation: does it belong to the household himself/herself, does it belong to some other 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), due to the hydrogeological variability in the area (Appendix 3), even hydrologic scientists cannot provide location-specific data on the parameter α, which summarizes the hydraulic properties of the aquifer, at the community level. Moreover, it would be difficult for water users in local communities to infer the exact magnitude of α. In order to explore the link between the nature of the aquifer and the rate of pumping, in the 2004 CWIM survey we asked community leaders several questions in order to identify some of the key characteristics of the aquifers. In particular, two questions were used: "Do you think pumping by households/community leaders in neighboring communities will affect the water level in your community?" and "Do you think your own pumping (or that of households in your community) will affect the water level in neighboring communities?" Of the 43 communities in Hebei and Henan province that were surveyed, 26 community leaders answered yes to both questions. Three community leaders answered yes to the first question but no to the second question. If a community leader answered yes to the first question, we define the community as a *Connected Community*. If a leader answered no, we defined the community as an *Isolated Community*.

Although the community leader's answer may have differed from the actual connectedness of the aquifers, since it is their perception upon which they rely on to guide their actions/decisions, we believe this way of categorizing communities is a reasonable way to model the behavior of water use characterized in the game theoretical models that were presented in the previous section. This is also consistent with the current status of groundwater management in rural China, where the formal regulatory framework is weak and hydrologists are not involved in the management of groundwater. 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.[11]

Estimation

In an earlier section, we developed a set of hypotheses to test the effects of different types of well management on the rate of pumping in communities that are connected and those that are isolated. From the decision rules developed in equation (2), (5), (7) and (9), the rate of pumping, w_t, can be summarized as $w(\alpha, I, S_t, N; \mathbf{M})$. That is, the rate of pumping is a function of the degree of connectedness of the community, α, the institutional arrangement (private or collective well management), I, the level of groundwater stock, S_t and the number of households that use a well, N. The vector $\mathbf{M}$ contains other exogenous factors that may affect the rate of pumping. The empirical objective is to estimate the function $w(S_t, \alpha, I; \mathbf{M})$ and use the estimation results to test the hypotheses.

Although we have used α to measure the degree of connectedness in the theoretical models, in reality, most community leaders do not know the exact value of α. The community

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[11] Similarly, Saak and Peterson (2007) also recognize that water users only have incomplete information on the parameter α and focus on analyzing the impact of the degree of uncertainty on the pumping behavior of users. Their finding is that under either complete or incomplete information regime, the non-cooperative pumping levels will exceed the efficient pumping levels. This is the hypothesis we will test later in our empirical analysis in the context of rural communities in China. Their other significant finding is that better information may either increase or decrease the equilibrium withdrawal. Unfortunately, we do not have data to empirically examine this finding.

leaders in our sample, however, can tell whether α is positive (the community is connected) or zero (the community is isolated). Hence, in the empirical analysis α is replaced by two aquifer dummy variables: the Connected dummy equals one for a connected community and zero otherwise; the Isolated dummy equals one for an isolated community and zero otherwise. Our data indicates that the nature of the aquifer varies across places. Among the wheat plots, 141 plots, more than 70% of the sample plots, are located in connected communities and other plots are in isolated communities (Table 1).

We generate 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 other wise; the Private dummy is the opposite of the Collective dummy. Among the wheat plots, 116 plots, almost 60% of the sample plots, draw water from wells that are privately managed (Table 1). This is consistent with the increasing trend of well privatization that is ongoing in northern China (Wang et al., 2006).

In order to control for the effect of the nature of the aquifer when comparing different well management, instead of using the dummy variables directly in estimation, we created 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 community and is irrigated by water from a collectively managed well. A Private-Isolated is a plot that is irrigated by water from a privately managed well and is located in an isolated community. Similarly, a Collective-Connected (Private-Connected) plot is a plot that is irrigated by water from a collectively (privately) managed well and is located in a connected community. All four groups of plots are present in our sample.

More than 40% of the sample plots are Private-Connected plots (Table 1). About 28% are Collective-Connected plots, 16% are Private-Isolated plots and 12% are Collective-Isolated plots.

In the empirical analysis, we also control for the cost of water. Most variation in the cost of water comes from the differences in the depth to water in wells across space. This can be seen by the strong positive correlation between the cost of water and the depth to water in one of the sample province, Hebei province (Table 2). Households that paid more for per unit of water are usually those that faced greater depth to water because it cost more to pump water out. For example, wheat-growing households in the fourth quartile (the households pumping from the deepest wells) paid as much as 0.50 yuan/m^3 for water; those households in the first quartile paid as little as 0.07 yuan/m^3 (column 2, row 2 and 5).[12] Since the depth to water in wells is probably closely related to the level of groundwater stock, S_t, and the cost of water is closely related to the depth to water, by including the cost of water in estimation, the effect of S_t is controlled for.[13]

The price of fertilizer is included in the vector **M**. Crop prices are not included since there is not much variation in them across households. Two additional sets of control 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), 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, the

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[12] Yuan is the unit of currency used in China—one dollar was about eight yuan in 2004 and dropped to about seven yuan in 2008.

[13] The simplifying assumption that the depth to water in wells is probably closely related to the level of groundwater stock is commonly used in the literature on the economics 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).

value of each household’s total assets and percentage of labor that is hired. Table 3 lists the definitions of the variables that are constructed from the data.

In summary, the following regression is estimated in order to examine the effects of different types of well management and the nature of the aquifer on the rate of water use:

$$\begin{aligned}\ln w = \beta_0 &+ \beta_1 Collectiveg\text{-}Connected + \beta_2 Private\text{-}Isolated + \beta_3 Private\text{-}Connected \\ &+ \beta_4 Cost_{Water} + \beta_5 N + \mathbf{M}\boldsymbol{\gamma} + \varepsilon\end{aligned} \tag{10}$$

where ε is the error term. The dependent variable, w, is in log form. The base group in equation (10) is the Collective-Isolated plots. Equation (10) is estimated using the method of Ordinary Least Squares (OLS).

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 the regulation by the community leader. If this is the case, the type of well management (private or collective) and the rate of pumping may be simultaneously determined. In such a case, well management may be endogenous if it is correlated with unobservable factors that are part of the error term (factors that are not included in the regression, but, that affect both well management and the rate of pumping). To check whether or not the estimates of our key parameters are possibly contaminated by bias due to endogeneity, during the survey we asked households to report (plot by plot) the number of wells from which they could obtain water to irrigate the plot. If a household had the choice to choose from several wells (and furthermore, and, if these wells were managed in different ways), we then would be even more concerned about the endogeneity of well management. Fortunately, the data show that out of the 196 sample plots, only 10 plots could be irrigated by water from more than one well.[14] That is, for

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[14] The sparse distribution of wells may be due to the well spacing limit imposed in some rural communities, that is, two wells within the same community have to be a certain distance apart, usually 300 m in rural China.

most of the sample plots, only one well was available to supply groundwater for irrigation. As a result, most households did not have the choice of using either collective or private wells. Based on this result, we do not believe that our estimated coefficients are biased (due to this endogeneity problem).[15]

Results

When we estimated the model defined by equation (10), the model performed well (Table 4, column 1). The adjusted R^2 is 0.397. The coefficients on most of the control variables have the expected signs. Most notably, the coefficient on the cost of water is negative and statistically significant. The coefficient on the price of fertilizer also is negative and statistically significant, which is expected since is it well known—e.g., Cai et al, (2008)—that water and fertilizer are complements in crop production. In addition, the coefficient on the variable that measures the distance from the plot to the well is positive, indicating that the volume of water pumped tends to increase as the distance increases.

The results of our estimation of our key parameters of interest show that the nature of the aquifer, in fact, does have a significant effect on the rate of pumping. Since the dependent variable of the regression 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, column 1, row 1).[16] Furthermore, since the dependent

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[15] The endogeneity of well ownership may also arise if households that want to pump more water decide to sink their own wells. For 41 plots in our sample, households irrigate the plots using water from their own wells. As a robust check, we estimate equation (10) without these plots. The results of estimation are reported in Appendix Table 1. The estimation results are largely the same as the results when the full sample is included in the regression. Most importantly, the magnitudes and statistical significance of the key variables, the interaction terms, are similar. Therefore, we do not believe that our estimated coefficients are biased (due to this endogeneity problem).

[16] Mu is the metric unit of land area that is used in China. 1 mu = 1/15 hectare.

variable is in log form and the independent variable is a dummy variable, the *exact* percentage difference is calculated as $\exp^{\beta} - 1$, where β 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 community use 27.5% ($\exp^{24.3} - 1$) more water than the plot in an isolated community. The percentage difference is measured in percentages of the rate of pumping on the base group plot and is statistically significant. This result supports Hypothesis 1a that the connectedness of a community will increase the rate of pumping, when other factors are held constant. The result also supports Hypothesis 1b but the evidence is not strong. The magnitude of the coefficient on the interaction term, Private-Connected, is 0.069 smaller than that on the interaction term, Private-Isolated (column 1, 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 community use 7.1% more water than the plot in an isolated community. The percentage difference, however, is smaller and not statistically significant.[17]

The results also support Hypothesis 2a. In isolated communities, the rate of pumping on a Collective-Isolated plot is reduced by 20.6% ($\exp^{-2.31} - 1$) from the level on a Private-Isolated plot (Table 4, column 1, row 3 and 4). This result shows that when we control for the effect of the nature of the aquifer on the rate of pumping, collective well management leads to resource conservation (which is exactly the prediction in Hypothesis 2a). The empirical results, however, does not support Hypothesis 2b.

The results also support Hypothesis 3. The percentage difference in connected communities, 5.5%, is not statistically different from zero. That is, empirical evidence from our

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[17] The percentage difference is smaller under private well ownership because the effect of the connectedness of a community on the private cost (the cost a household pays under private well ownership, the RHS of equation 7 and 9) is much lower than the effect on the social cost (the cost a household pays under collective well ownership, the RHS of equation 2 and 5).

data shows that in connected communities, collective well management does not save water. In contrast, in isolated communities, 20.6% of the water is saved under collective well management. In short, collective well management is much more effective in conserving water resources in isolated communities than in connected communities, which is exactly what is predicted by Hypothesis 3. The implications of this, which is discussed more below, is that one way China could consider improving efforts at conservation would be to redefine the unit of resource management to be more consistent with the nature of the aquifer. In other words, if two or more communities are connected, there may need to be a new institutional arrangement set up (e.g., a multi-community Water User Association) to manage pumping from the aquifer.

In order to test Hypothesis 4, we estimate an alternative specification in Table 4 (column 2). In this specification, we do not control for the nature of the aquifer. That is, the two dummy variables, Connected and Isolated, are removed from the regression. Only the well management dummy, Private, is included in the regression. The base group is now the plot under collective well management. The coefficient on the variable Private shows that on average plots that are irrigated by water from privately managed wells use 11.4% more water than plots that are irrigated by water from collectively owned wells (Table 4, column 2 and row 4). This percentage difference is much smaller than 20.6%, the percentage difference in isolated community. Clearly the results without controlling for the nature of the aquifer under-estimates the potential of collective well management in conserving water by almost 50%. This is because the coefficient on the variable Private mixed the comparison in isolated communities (where the difference between collective and private well management is large) and the comparison in connected communities (where there is no difference between collective and private well management). Importantly, insights from the results of Tables 4 may explain at least part of the puzzling results in previous studies (e.g., Wang et al., 2005, which found little difference between private and collective wells).

Conclusions

In this paper, we compare the effectiveness of collective well management and private well management in managing groundwater resources. Most importantly, we take into account the nature of the aquifer, that is, whether or not the aquifer underlying a community is connected to or isolated from the aquifers underlying neighboring communities. Three implications can be drawn from this study. First, community-based management of groundwater resources has the potential to succeed in resource conservation. In our study areas, when households in an isolated community obtain irrigation water from collectively managed wells, the community leader, who is in charge of allocating water among households, has a relatively strong incentive to conserve water. Our results show that households in isolated communities and under collective well management use 20% less water than households also in isolated communities but under private well management, even after factors such as the cost of water per unit, plot size and soil type are controlled for. Therefore, at least in rural China, the community with an isolated aquifer has the potential to achieve cooperative extraction, a key determinant of the success of CPR management.

Second, whether community-based management of groundwater resources is adequate for resource conservation depends crucially on the nature of the aquifer. The administrative boundary of a community often does not match with that of the aquifer. Our results show that when such mis-matches exist, the incentives of communities to conserve water are undermined. Specifically, when a community’s aquifer is connected to those of neighboring communities, there is no difference in the rate of pumping between households under collective well management and households under private well management. When a community is hydrologically isolated, the management of groundwater may be left to the community itself. However, when a community is not hydrologically isolated, the success of community-based management would depend on cooperation within community households as well as cooperation among communities that share the connected aquifers. Therefore, future research should also focus on studying the factors that can lead to cooperation among communities. 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 mis-match between administrative boundary and natural resource boundary is also common for other types of CPRs (e.g., such as 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. Partly because of the lack of hydrology information at the community level, we have only relied on the perception of community 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 only based 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 community level. Our results show that the collective well management and private well management have generated different resource outcomes. Therefore, the success of community-based management also depends on the specific institutional arrangement. This point is also important in management of other types of CPRs. For example, Sakurai et al. (2004) compared the collective management and individual management of Nepal’s community forestry and also found significant differences.

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Table 1. Household plots under different well management and in different communities in Hebei and Henan Provinces, 2004

	Connected communities	Isolated communities	Total
Collective well management	56 (28.6)	24 (12.2)	80 (40.8)
Private well management	85 (43.4)	31 (15.8)	116 (59.2)
Total	141 (72)	55 (28)	196

†Percentages are reported in parentheses.

Table 2. The cost of water and the depth to water in wells in Hebei Province, China 2004

Percentile of the cost of water		(1) Depth to water (m)	(2) Average cost of water (yuan/m^3)
1	Average	38.4	0.24
2	0-25%	15.9	0.07
3	26-50%	19.4	0.16
4	51-75%	51.9	0.26
5	76-100%	69.0	0.50

†Yuan is the unit of currency used in China—one dollar was about eight yuan in 2004 and dropped to about seven yuan in 2008.

Table 3. Variable definitions

1	Collective-Connected	Interaction dummy (=1 if a plot is irrigated by water from a *collectively* owned and managed well and is located in a *connected* community)
2	Private-Isolated	Interaction dummy (=1 if a plot is irrigated by water from a *privately* owned and managed well and is located in an *isolated* community)
3	Private-Connected	Interaction dummy (=1 if a plot is irrigated by water from a *privately* owned and managed well and is located in a *connected* community)
4	Collective-Isolated	Interaction dummy (=1 if a plot is irrigated by water from a *collectively* owned well and managed and is located in an *isolated* community)
5	Private:	Well ownership dummy (=1 if the plot draws water from a private well)
6	Water cost, log:	Log of water cost measured in yuan per m^3
7	N:	Number of households the well irrigate
8	Fertilizer price, log:	Log of fertilizer price measured in Yuan / Jin. 1 Jin = 0.5 Kg
9	Sand:	A dummy, =1 if soil type is sand and 0 if soil type is loam or clay
10	Plot size, log:	Log of plot size in mu (1 hectare = 15 mu)
11	Distance:	Distance from the plot to the well measured in km
12	Lined:	Percentage of the conveyance route that is lined, %
13	Irrigation method:	A dummy variable, =1 if the plot is irrigated using flooding
14	Age:	Average age of schooling of household households in the household
15	Education:	Average years of schooling of household households in the household
16	Household asset:	Total household asset, measured 1,000 yuan
17	Hired labor:	Percentage of hired labor used on the plot, %
18	Hebei dummy	A dummy variable, = 1 if the plots are from Hebei province, = 0 if the plots are from Henan province.

Table 4. The effect of well management and the nature of the aquifer on the rate of pumping

Dependent variable: Log of the volume of water pumped per mu, m^3/mu

		(1)		(2)	
	Base Group	**Collective-Isolated**		**Collective (Isolated or Connected)**	
1	Collective-Connected	0.243***	(0.0623)		
2	Private-Connected	0.300***	(0.0602)		
3	Private-Isolated	0.231***	(0.0673)		
4	Private			0.108***	(0.0390)
5	Water cost, log	− 0.169***	(0.0193)	− 0.174***	(0.0200)
6	*N*	− 0.000150	(0.000537)	− 0.000157	(0.000557)
7	Fertilizer price, log	− 0.0690*	(0.0381)	− 0.0765*	(0.0396)
8	Sand	0.0573	(0.0397)	0.0492	(0.0413)
9	Plot size, log	− 0.0575***	(0.0216)	− 0.0439**	(0.0222)
10	Distance	0.000150*	(0.0000889)	0.0000674	(0.0000899)
11	Lined	− 0.0000117	(0.000378)	0.000500	(0.000370)
12	Irrigation method	0.0205	(0.0456)	0.0365	(0.0472)
13	Age	0.000232	(0.00174)	− 0.000662	(0.00179)
14	Education	0.00239	(0.00807)	− 0.00269	(0.00827)
15	Household asset	− 0.000396	(0.000504)	− 0.000114	(0.000517)
16	Hired labor	− 0.00107	(0.00160)	− 0.000589	(0.00165)
17	Hebei Dummy	0.0560	(0.0526)	0.0498	(0.0544)
18	Constant	5.464***	(0.132)	5.646***	(0.129)
	Number of observations	196		196	
	Adjusted R^2	0.397		0.348	

Standard errors in parentheses; *, **, *** significant at 10%, 5% and 1%, respectively

Appendix Table 1. The effect of well management and the nature of the aquifer on the rate of pumping, without the plots that are irrigated by the wells owned by the same households

Dependent variable: Log of the volume of water pumped per mu, m^3/mu

	Base Group	**Collective-Isolated**	
1	Collective-Connected	0.216***	(0.0573)
2	Private-Connected	0.327***	(0.0590)
3	Private-Isolated	0.216***	(0.0632)
4	Water cost, log	− 0.241***	(0.0229)
5	*N*	− 0.000517	(0.000541)
6	Fertilizer price, log	− 0.0732**	(0.0366)
7	Sand	0.0356	(0.0410)
8	Plot size, log	− 0.0575**	(0.0235)
9	Distance	0.0000630	(0.0000878)
10	Lined	0.000257	(0.000393)
11	Irrigation method	0.00169	(0.0481)
12	Age	0.00133	(0.00199)
13	Education	− 0.00105	(0.00810)
14	Household asset	0.0000781	(0.000517)
15	Hired labor	− 0.00235	(0.00178)
16	Hebei Dummy	0.141**	(0.0545)
17	Constant	5.276***	(0.146)
	Number of observations	155	
	Adjusted R^2	0.549	

a. Standard errors in parentheses; *, **, *** significant at 10%, 5% and 1%, respectively.

b. For 41 plots in our sample, households irrigate the plots using water from their own wells. We estimate the same equation as in Table 4 but without these 41 plots. So the number of observation is different from that in Table 4.

Appendix 1. Location and Hydrogeology of the Study Area

The study areas in this paper, in Hebei and Henan provinces, are located in northern China (Figure 1). Hebei province (the black area in the map) covers most of the Hai River Basin and surrounds Beijing. Henan province (the grey area in the map) is located in the middle reaches of the Yellow River Basin.

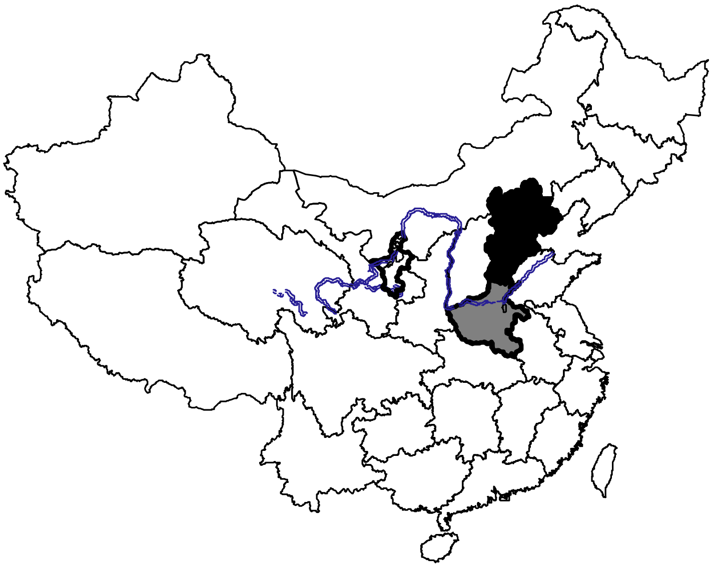

Figure 1. The map of China and the study areas

The climate in the area is semi-arid. From the foot of the mountains (in western Hebei) to the coastal area, Hebei province can be divided into a alluvial flood plain (western part), and flood and lake sedimentary plain (middle part); and an alluvial coast plain (eastern part—(Figure 2, Foster, et al., 2004). Vertically, aquifers in Hebei province are divided into four aquifers 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). Similarly, in Henan province groundwater also occurs in multi-layers of aquifers, a top unconfined layer, a middle semi-confined layer and a bottom confined layer (Manouchehr et al., 1996). Figure 8 and Figure 9 in Wang et al. (2008) provide a cross section of the hydrogeological structure of the area.

Most relevant to our analysis, transmissivity varies greatly across different parts of the aquifers in both 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 wells as types of materials (e.g., sand, gravel or clay) in different parts of aquifers (Fig. 8 and Fig. 9 in Wang, et al., 2008). As a result, aquifers in the study area cannot be characterized as bathtub or single cell aquifer, which assumes instantaneous lateral flow of groundwater between a water user and his/her neighboring users.

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

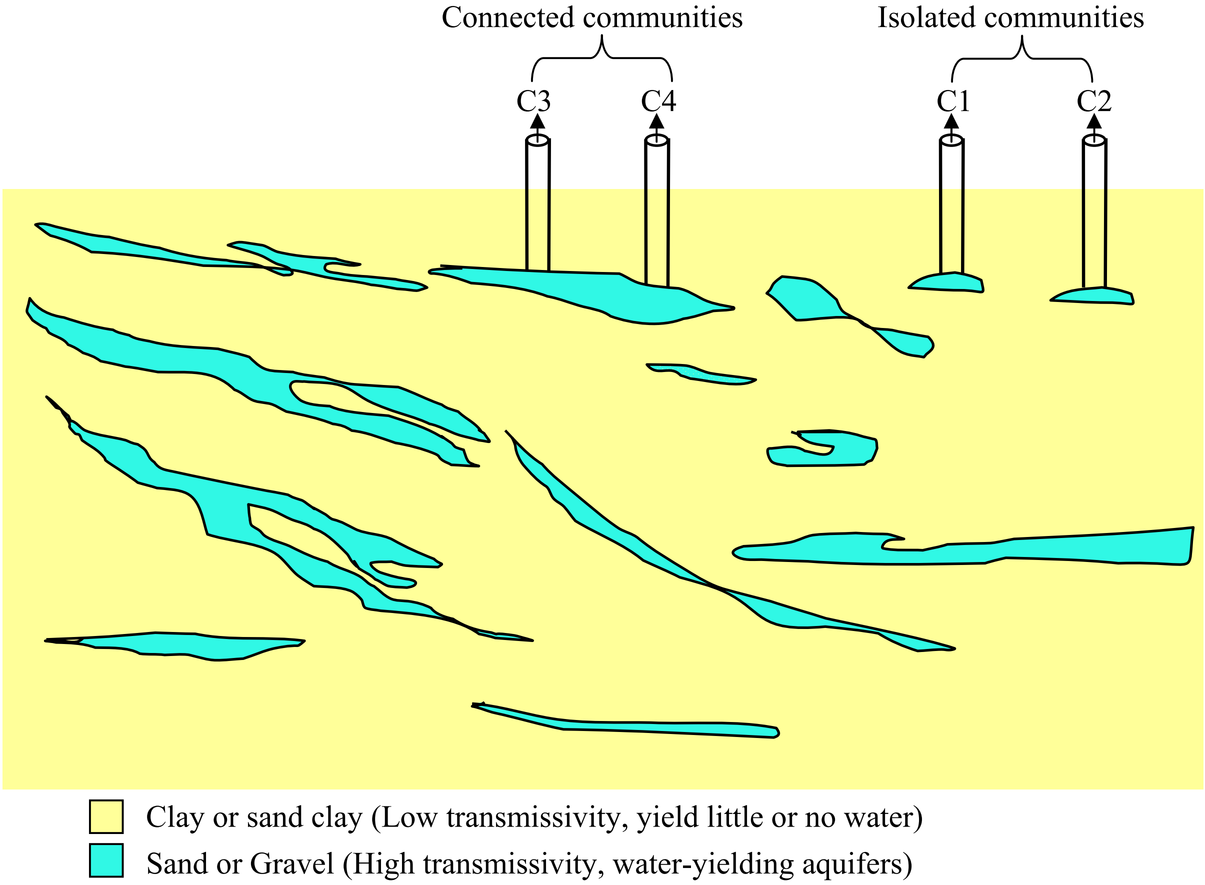

Figure 2. Illustration of isolated and connected communities

Appendix 2. Deriving Hypothesis 1a

Saak and Peterson (2007) have proved results that are similar to hypothesis 1a. When there are lateral groundwater flows between the wells of two farmers (that is, wells are connected) and when farmers are not regulated, each farmer will pump more than the efficient level, which is the level of pumping each individual farmer will choose to maximize his individual benefit when the wells are not connected. The result does not change whether each farmer has complete or incomplete information about the speed of the flow. More general case has also been proved in Eswaran and Lewis (1984). When there is seepage of the resource (most often, the resource is oil) between the fields (that is, the fields are connected), a greater proportion of the existing stock is extracted each period as the seepage increases.

In this appendix, we derive hypothesis 1a following the approach used in Levhari and Mirman (1980) and Eswaran and Lewis (1984) but adapting it to our specific problem at hand. The method of backward induction is used to solve the Bellman equation. For the sake of simplicity, we suppress the notation for households and only focus on the community. Let W_t be the aggregate pumping of community 1 at time t. Further we assume the instantaneous benefit accruing to community 1 at time t, $B(W_t)$ is quadratic:

$$B(W_t) = aW_t - b(W_t)^2 \qquad \text{(A2.1)}$$

where a and b are positive constants. And the unit cost is a linear function of the groundwater stock:

$$C(S_t) = c - dS_t \qquad \text{(A2.2)}$$

where c and d are positive constants.

We begin with the last period of pumping, T. The community leader is solving the problem:

$$Max\ \bar{V}_T = aW_T - b(W_T)^2 - (c - dS_T)W_T \qquad \text{(A2.3)}$$

Where $\bar{V}_T$ is the sum of the value function of all N households in the community, NV_T. Taking the partial derivative with respect to W_T, we obtain the level of pumping of community 1:

$$W_T^* = a - (c - dS_T)/2b \qquad \text{(A2.4)}$$

Substituting (A2.4) back into (A2.3) gives the optimized value function at time T:

$$\bar{V}_T^* = \left[a - (c - dS_T)\right]^2 \big/ 4b \qquad \text{(A2.5)}$$

Now go back in one period and the leader is solving the problem at time $T - 1$:

$$\begin{aligned} Max\ \bar{V}_{T-1} &= B(W_{T-1}) - C(W_{T-1}) + \delta V_T \\ &= aW_{T-1} - b(W_{T-1})^2 - (c - dS_{T-1})W_{T-1} + \delta\left[a - (c - dS_T)\right]^2 \big/ 4b \qquad \text{(A2.6)} \\ s.t. \quad S_T &= S_{T-1} - W_{T-1} + \alpha[W_{T-1} - W_{T-1}^{2*}] = S_{T-1} - (1-\alpha)W_{T-1} - \alpha W_{T-1}^{2*} \end{aligned}$$

Taking the partial derivative with respect to W_{T-1}, we obtain the first order condition:

$$a - 2bW_{T-1} - (c - dS_{T-1}) - (1-\alpha)d\delta\left[a - (c - d(S_{T-1} - (1-\alpha)W_{T-1} - \alpha W_{T-1}^{2*}))\right] \big/ 2b = 0 \qquad \text{(A2.7)}$$

Suppose community 1 and 2 are identical and both communities begin with the same level of groundwater stock at $T - 1$, then it is easy to show that the level of W_{T-1}, $W_{T-1}^* = W_{T-1}^{2*}$. With the symmetric equilibrium, we have:

$$W_{T-1}^* = \left[a - (c - dS_{T-1})\right]\left(2b + (\alpha - 1)d\delta\right) \big/ \left[4b^2 + (\alpha - 1)d^2\delta\right] \qquad \text{(A2.8)}$$

For W_{T-1}^* to be nonnegative, it is necessary that the following condition on the parameters be satisfied:

$$a - (c - dS_{T-1}) \geq 0 \qquad \text{(A2.9)}$$

In addition, W_t cannot exceed the level of available groundwater stock, S_t, in any time period. This relationship requires the following condition on the parameters:

$$2b \geq d \tag{A2.10}$$

Differentiating (A2.8) with respect to *α*, we obtain:

$$\partial W_{T-1}^{*} \big/ \partial \alpha = 2bd\delta\left[a-(c-dS_{T-1})\right]\left(2b-d\right) \Big/ \left[4b^2+(\alpha-1)d^2\delta\right]^2 \tag{A2.11}$$

The parameters *b*, *d*, *δ* (the discount factor) are all positive. In addition, condition (A2.9) and (A2.10) indicate other terms in (A2.11) are positive. Therefore, $\partial W_{T-1}^{*} / \partial \alpha > 0$. That is, the aggregate level of pumping in community 1 increases as *α* increases. Since the pumping of individual household, $w_{T-1}^{*} = W_{T-1}^{*} / N$, and *N* does not change with *α*, each individual household also pumps more as *α* increases. We can use the same backward induction technique and prove the same results for other time periods. In short, when *α* increases from zero to be positive, that is, when community 1 changes from being isolated to connected (while holding other factors constant), the leader will increase the aggregate level of pumping. As a result, each individual household also pumps more.

Appendix 3.

In Appendix 2, we have derived that the rate of pumping that maximizes the value function of community 1 at time $T-1$ is $W^*_{T-1} = \left[a-(c-dS_{T-1})\right]\left(2b+(\alpha-1)d\delta\right)\Big/\left[4b^2+(\alpha-1)d^2\delta\right]$ (equation A2.8 in Appendix 2). Let $\varphi = \left(2b+(\alpha-1)d\delta\right)\Big/\left[4b^2+(\alpha-1)d^2\delta\right]$. Substituting (A2.8) into (A2.6) gives the optimized value function at time T:

$$\begin{aligned}\bar{V}^*_{T-1} &= \left[a-(c-dS_{T-1})\right]W^*_{T-1} - b(W^*_{T-1})^2 + \delta\left[a-(c-dS_T)\right]^2\Big/4b \\ &= \left[a-(c-dS_{T-1})\right]^2\left\{\varphi - b\varphi^2 + \delta(1-d\varphi)^2/4b\right\}\end{aligned} \tag{A3.1}$$

Differentiating (A3.1) with respect to S_{T-1} gives the marginal value of one more unit of groundwater stock:

$$\partial\bar{V}^*_{T-1}\big/\partial S_{T-1} = 2d\left[a-(c-dS_{T-1})\right]\left\{\varphi - b\varphi^2 + \delta(1-d\varphi)^2/4b\right\} \tag{A3.2}$$

Differentiating (A2.2) with respect to α gives

$$\frac{\partial\left[\partial\bar{V}^*_{T-1}\big/\partial S_{T-1}\right]}{\partial\alpha} = -\,4\alpha d^4\delta^2\left[a-(c-dS_{T-1})\right]^2\left(2b-d\right)^2\Big/\left[4b^2+(\alpha-1)d^2\delta\right]^3 \tag{A3.3}$$

The parameters α, b, d, and δ are all positive constants. The condition (A2.10) implies $\left[4b^2+(\alpha-1)d^2\delta\right]^3>0$. In addition, other terms in (A3.3) are quadratic and thus are positive. Therefore, $\dfrac{\partial\left[\partial\bar{V}^*_{T-1}\big/\partial S_{T-1}\right]}{\partial\alpha} < 0$. That is, the marginal value of one more unit of groundwater stock decreases with α. It follows naturally that $\partial\tilde{V}_{t+1}(S_{t+1})\big/\partial S_{t+1}$ for a connected community (when $\alpha > 0$), is smaller than $\partial V_{t+1}(S_{t+1})\big/\partial S_{t+1}$ in an isolated community (when $\alpha = 0$).