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Agriculture and groundwater development in northern China: trends, institutional responses, and policy options

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Abstract

Despite the growing importance of groundwater in Chinese agriculture, there is a lamentable lack of systematic information on the groundwater economy, especially on the agricultural consequences of groundwater depletion. This paper makes an attempt to overcome this limitation with information and analysis on trends in the expansion of agricultural groundwater use, resource management challenges, and institutional and policy responses in the particular context of northern China. The results show that groundwater problems and their agricultural consequences in northern China are heterogeneous across space and changing rapidly over time. While the problems are serious, they do not present everywhere with the same severity. As result, policies for their solution should be clearly discriminatory and carefully targeted. Even targeted policies will be difficult to implement, and government has had little success in controlling the extraction of groundwater or protecting its quality with the many formal laws and regulations now in existence. In contrast, farmers have been responsive to increasing shortages. Individual farmers (i.e. the private sector) have taken control of most well and pump assets, developed groundwater markets, changed cropping patterns and adopted water savings technologies. While market forces and economic incentives can change use, public initiatives for agricultural groundwater regulation to balance short term economic efficiency with long resource sustainability are urgently needed.

Keywords: Development; Groundwater resources; Institutional Responses; Northern China; Policy

Introduction

The development of the groundwater sector in China has a history of less than 50 years and has played an increasingly important role in the growth and expansion of Chinese agriculture. Groundwater use, which

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was almost zero in the 1950 s, rose to 57 billion cubic meters (bcum) annually in the 1970s (Ministry of Land Resources, 2005). Groundwater use continued to expand, especially after the economic reform in the late 1970 s, reaching 75 bcum in the 1980s and more than 100 bcum at present, equivalent to approximately twice the annual flow of the Yellow River. The share of groundwater in the total water utilization of China has also increased from almost nothing in the 1950s to more than 20% in the early 2000s (Ministry of Water Resources & Nanjing Water Institute, 2004). However, this share is uneven, with only 14% in southern China and 49% in northern China, where groundwater was, and is, critical for the emergence and expansion of agriculture in particular and the regional economy in general.

Unfortunately, the intensive use of groundwater has also created many environmental problems, in particular related to overdraft in northern China (Ministry of Water Resources & Nanjing Water Institute, 2004). In the late 1990s, for instance, the annual rate of overdraft exceeded 9 bcum, leading to water table decline, seawater intrusion, and land subsidence. The problem is widespread as the decline in water tables was observed in 48% of villages in six provinces of northern China (Wang *et al.*, 2005). With falling water table, pumping costs have risen by 0.005 yuan per cubic meter and, in many cases, agricultural wells have been abandoned and replaced by new deeper tubewells. Equally serious is the environmental problem of declining water quality (Nickum, 1988; Ministry of Water Resources & Nanjing Water Institute, 2004).

Despite the increasing importance of groundwater and the economic and environmental consequences of its over-exploitation, there is a lamentable dearth of systematic studies, especially on the policy and institutional options for the regulation and management of the groundwater economy in China. Most of the available studies in English deal primarily with groundwater usage and the attendant resource-related problems such as the water table decline and water quality deterioration discussed above (e.g. Tang, 1999; Chen *et al.*, 2003; Sakura *et al.*, 2003; Kendy *et al.*, 2003). Many other studies are general summary pieces based primarily on anecdotes and secondary citations (e.g. Nickum, 1988; Lohmar *et al.*, 2003). There are few recent works (e.g. Wang *et al.*, 2005, 2006a, b) that address the specific aspects of institutional responses, especially with data from large scale farm or household surveys. This paper adds to this limited but important set of studies with an analysis of original data sufficiently broad in scope both to provide a general overview of the trends and issues in the development and use of groundwater for agriculture as well as to highlight the coping strategies and institutional options.

With particular emphasis on agricultural water use, the specific objectives of this paper are to: (a) characterize China's groundwater resources and track their development over space and time; (b) examine the government's groundwater policies related to agricultural use and evaluate their effectiveness; (c) document the institutional responses of farmers and community leaders in areas that are facing acute groundwater problems; and (d) use the results and analysis to derive policy insights for the sustainable use and management of groundwater resources in particular and water resources in general for agricultural development in China.

Methodology and data

Broad-scale published data on Chinese groundwater users and the institutions that govern them is extremely limited. The analysis presented here is based mainly on our own primary data collected as part of two recent surveys specifically designed to examine irrigation practices and agricultural water management. The first survey, the China Water Institutions and Management survey (CWIM), was conducted in September 2004. Enumerators conducted surveys of community leaders, groundwater managers, surface water irrigation managers and households in 48 villages in Hebei and Henan provinces. The 2004 CWIM survey built on a similar survey conducted in 2001.

The study team also conducted a second survey, the North China Water Resource Survey (NCWRS), in December 2004 and January 2005. This survey of village leaders from regionally representative villages in Inner Mongolia, Hebei, Henan, Liaoning, Shaanxi and Shanxi provinces used an extended version of the community level village instrument of the CWIM survey. Using a stratified random sampling strategy for the purpose of generating a sample representative of northern China, counties in each province were sorted into one of four water scarcity categories: very scarce, somewhat scarce, normal and mountain/desert. Two townships within each county and four villages within each township were also randomly selected. In total, the data collection team visited 6 provinces, 60 counties, 126 townships and 448 villages. The survey collected data on most variables for two years, 2004 and 1995.

The scope of these surveys was quite broad. Each of the survey instruments included more than 10 sections, including sections focused on the nature of rural China's water resources and groundwater problems. Several sections examined government policies and regulations, such as the system of issuing well drilling permits, groundwater resources fees and government promotion of water management reform and water saving technology. Other sections examined institutional responses by farmers, including the privatization of tubewells, groundwater markets, water pricing and adoption of water saving technologies. Additional information on the survey and methodology can be found in Wang *et al.* (2006a, b) and Blanke *et al.* (2006).

Agricultural use of groundwater: nature, pattern, and consequences

Groundwater resources in China are unevenly distributed and utilized across regions. According to the latest estimates generated by the Ministry of Land Resources, the annual natural recharge of fresh groundwater resources in China is 884 billion cubic meters and groundwater resources account for about one third of the nation's total water resources (Ministry of Land Resources, 2005). About 70% of groundwater resources are located in southern China, leaving only about 30% in northern China. However, the intensity of groundwater use occurs in a much different pattern. Rural and urban users in northern China are using more than 70% of known groundwater resources in the region. In contrast, less than 30% of the known groundwater resources in southern China are being used.

Groundwater aquifers: diversity and extraction pattern

Relying on the observations of respondents from the NCWRS datasets, one of our most prominent findings is the diversity of aquifer development in northern China. Of the 238 sample villages that used groundwater for irrigation in 2004, 33% reported that they extract groundwater only from shallow aquifers, and 42% only from deep aquifers. The data show that, in some villages in northern China, the groundwater supply from shallow aquifers is sufficient to support current local water demand for irrigation. In other villages, perhaps due to exhausted or unusable shallow aquifers, farmers extract groundwater only from deep aquifers. In some villages (25%), both shallow and deep aquifers are being used.

Whether deep or shallow, groundwater resources are extensive across regions of northern China. Most villages in northern China have groundwater; the share of irrigated villages having groundwater resources was almost 95% in 2004. However, not all villages with groundwater use this resource for irrigation. In 2004, more than 15% of irrigated villages with groundwater did not use it to irrigate. Although it could be that in some cases groundwater is not readily accessible (it is there but too deep to be extracted economically), our findings suggest that in the future it may be possible to use even greater volumes of groundwater in some areas. Such a conjecture is supported by the recent growth of groundwater usage: over the past ten years, with increasing water scarcity and rising water demand, more villages have begun to use their community's groundwater. For example, between 1995 and 2004, the share of villages using groundwater resources *for the first time* increased by almost 12%.

Regional differences in water table decline

Although the fall of the water table has been called one of the most serious environmental problems in northern China (World Bank, 1997), this problem does not exist everywhere in the region. According to our data, groundwater resources have shown little or no decline since the mid-1990s in 35% of northern China's villages using groundwater over the past decade. In another 16% of villages, respondents told the enumerators that the groundwater was actually higher in 2004 than in 1995. Hence, based on our data, most villages are either in balance or close to being in balance. However, we are not arguing that groundwater problems do not exist. In fact, there are a large number of villages (48%) in which the water table is falling. If we follow the definition of the Ministry of Water Resources (MWR) of water tables that are in "serious overdraft" (that is, the rate of decline exceeds 1.5 meters per year), 8% of villages using groundwater are in serious overdraft.

In summary, in many places in northern China – indeed, in most – it is possible that water resources are not being misused. However, we do not want to minimize the problems that are occurring in some areas. The water table appears to be falling at a dangerously fast pace in a large number of rural areas. Where the resource is being misused, it is almost certain that measures will be required to protect the long run value and availability of the resource. However, many of the required measures which will be required to obtain related policy goals, such as water saving technology adoption, sustainable agricultural productivity and avoiding reduced income, have a cost associated with their execution. Because measures to counter overdraft are not needed in all villages, leaders should not take a "one-size-fits-all" approach so as to avoid unnecessary costs on producers where overdraft conditions do not exist.

Tubewell expansion and groundwater extraction

According to national statistics, the installation of tubewells began in the late 1950s and, although the number of wells has grown continuously, the pace of increase has varied from decade to decade (Ministry of Water Resources & Nanjing Water Institute, 2004). During the 1950 s, the first pumps were introduced to China's agricultural sector. Although still fairly limited, the growth rate of pump installation was rapid. Around the Great Leap Forward from the late 1950s to the early 1960 s, however, statistical reporting was unreliable and many irrigation projects that were started were badly engineered and often abandoned. After the recovery from the Great Leap Forward and the famine that followed, statistical agencies also recovered and statistical series since the mid-1960s have been more reliable and consistent.

Since the mid-1960s the installation and expansion of tubewells across China has been nothing less than phenomenal. In 1965 there were only 150,000 tubewells in all of China (Shi, 2000). Since then the number has grown steadily. By the late 1970s there were more than 2.3 million tubewells. After a period of stagnation from the early to the mid-1980 s, a period of time when irrigated area decreased, especially that serviced by surface water, the number of tubewells continued to rise. By 1997 there were more than 3.5 million tubewells; by 2003, the number rose to 4.7 million (Ministry of Water Resources, 2004).

The path of tubewell expansion shown in the official data is largely supported by the information we have from the NCWRS. Enumerators asked village leaders for the initial year in which someone (either the village leadership or an individual farmer) in his/her village sank a tubewell (Table 1). According to these data, by 1960 less than 6% of villages had sunk their first tube well. Over the next twenty years, between the early 1960s and the onset of reform, the percentage of villages with tubewells rose to more than 50%. During the next ten years, between 1982 and 1992, the number of villages with tubewells rose by only 7%. After the early 1990 s, however, the pace of the expansion of groundwater use accelerated, and by 2004, almost 75% of villages had wells and thus were using groundwater for irrigation.

Government role in groundwater management

Modern China has built on its long history of water management to construct a vast and complex bureaucracy to manage its water resources. To understand the functioning of this system, it is important to first understand that, until recently, neither use of groundwater nor conservation of water in general was ever of major concern to policymakers. Instead, the system originally was designed to construct and manage surface water to prevent floods, which have historically devastated the areas surrounding major rivers, and to effectively divert and exploit water resources for agricultural and industrial development. Historically, when attention was paid to water conservation, the emphasis was

Table 1. Share of villages with tubewells over time in northern China's villages, 1949–2004.

Year	Share of villages with tubewells (%)
1955	1
1960	5
1965	18
1970	32
1975	44
1980	50
1985	56
1990	58
1995	62
2000	71
2004	74

Data sources: Authors' survey in 2004 (NCWRS dataset).

on surface water canal networks. Indeed, China's success in using surface water resources is largely to blame for water shortages that the nation faces today: it has effectively tapped most of northern China's existing surface water resources. Government policy has yet to directly address many of the most severe groundwater problems.

Effectiveness of laws and policies

Water policy is ultimately created and theoretically executed by the Ministry of Water Resources (MWR). The MWR has run most aspects of water management since China's first comprehensive Water Law was enacted in 1988, taking over the duties from its predecessor, the Ministry of Water Resources and Electrical Power. The administrative power of MWR's water management has been further strengthened with the issuing of a revised Water Law in 2002. The MWR's policy role is to create and implement national price and allocation policy, to oversee water conservancy investments by providing technical guidance, and to issue laws and regulations to the sub-national jurisdictions and agencies (Lohmar *et al.*, 2003).

Officials in the MWR and in other ministries have spent time and effort to pass laws concerning groundwater management. For example, according to China's national Water Law, all property rights to groundwater resources belong to the state. This means that the right to use, sell and/or charge for water ultimately rests with the government. The law does not allow groundwater extraction if pumping is harmful to the long run sustainability of groundwater use.

Beyond the formal laws, a number of policy measures have been set up, in part, to rationally manage use of the nation's groundwater resources. Since the early 1990s, more than 40 water regulations have been issued by the MWR. However, this number is limited in comparison to the number of regulations concerning other issues, such as flood control, the construction of water-related infrastructure projects and surface water management initiatives. There are two important regulations related to groundwater management – one on the issue of permitting groundwater extraction, and one on the use by local governments of water resource fees. More importantly at the national level, there is not one water regulation that is specifically focused on groundwater management issues. Although there are a limited number of national regulations on groundwater management, in most provinces, prefectures and counties there are – at least on paper – also some local regulations controlling the right to drill tubewells and the spacing of tubewells.

Even more important than the lack of official laws and policy measures on groundwater management has been the insufficient effort put into implementing existing laws. Certainly, part of the problem is historic neglect. In fact, at the ministerial level, the division of groundwater management is still relatively small. There are far fewer officials working in this division than in other divisions, such as flood control, surface water system management and water transfer. Moreover, unlike the case of surface water management (Lohmar *et al.*, 2003), there has been no effort to bring management of aquifers that span jurisdictional boundaries under the ultimate control of an authority with control over the government and private entities that use water extracted from different parts of the aquifer. According to Negri (1989), without a single body controlling the entire resource, it becomes difficult to implement policies that attempt to manage the resource in a manner that is sustainable, or optimal, in the long run.

Whether due to lack of personnel or other implementation-related difficulties, few regulations have had any affect inside China's villages. For example, according to our survey data, less than 10% of well owners obtained a well drilling permit before drilling, despite the nearly universal regulation requiring a permit. Only 5% of village respondents believed that well drilling decisions required consideration of well spacing. Even more tellingly, water extraction charges were not charged in any village, and there were no quantity limits put on well owners. In fact, in most villages in China, groundwater resources are almost completely unregulated. This does not mean, however, that agricultural groundwater use is not impacted by policy and governance, at least indirectly.

Farmers initiatives in local groundwater management

Although China's central and local governments currently have little control over groundwater in most parts of northern China, groundwater governance is not stagnant. In fact, various aspects of groundwater management, including the way farmers gain access to water, the responses of farmers to increasing water pricing and the way technology is being used to conserve water, are all extremely dynamic. In this subsection, we examine four sets of issues: the privatization of tubewells; the emergence of groundwater markets; and the response of farmers to increasing water prices and the adoption of new, water-saving technologies.

Privatization. The privatization of tubewells is perhaps the most prominent feature of groundwater governance in northern China (Wang *et al.*, 2006a). Before the rural reforms in the 1960s and 1970s township governments and village leadership councils financed, owned and managed most tubewells. In most villages individual farmers contributed only labor for tubewell construction, if they contributed anything at all. Financed primarily by collective retained earnings, commune, brigade and team cadres were largely responsible for arranging for the water resource bureau-run well drilling companies to sink tubewells. Pumps in the pre-reform era all came from either the water resource bureau pump supply companies or the state-run local agricultural inputs corporation.

Soon after the general economic reforms began in the early 1980s, however, the ownership of China's tubewells began to shift sharply. According to a survey in Hebei Province in the late 1990s, 93% of all tubewells were owned by collectives in the early 1980s (Wang *et al.*, 2006a). However, collective ownership of tubewells diminished throughout the late 1980s and 1990s. During this period the share of private tubewells increased from 7 to 64%. Data from the NCWRS largely support these findings. Tubewell ownership in our study area, representative of northern China, has also shifted sharply from collective to private. In 1995, collective ownership accounted for 58% of tubewells in the average groundwater-using village. From 1995 to 2004, however, collective ownership of tubewells diminished and accounted for only 30% of wells in 2004. In contrast, during the same period the share of private tubewells increased from 42 to 70%.

Interviews by the authors revealed that the shift of tubewell ownership is the result of the establishment of new tubewells through the rise of privately-financed investment, rather than ownership transfer of collective tubewells. Some collective tubewells became inoperable during the past two decades, due to falling water tables and lack of maintenance of pumps and engines, and so the absolute number of collective tubewells fell. In contrast during this time, the number of private wells has increased rapidly.

Pump ownership has shifted from collective to private at an even faster rate than the privatization of tubewells. Data from NCWRS indicate that collective ownership accounted for 29% of pumps in the average groundwater-using village in 1995 as compared to 58% of tubewells. Our survey found that some pumps used with collectively-owned tubewells were privately held by individual farmers, rather than by the collective. This may be the primary explanation for the rapid privatization of pumps relative to tubewells. Between 1995 and 2004, the share of collective ownership of pumps fell to a mere 17%, while the share of private pumps grew from 71 to 83%.

In addition to ownership, management responsibility for tubewells also has devolved from collective to individual farmers. Data from NCWRS indicate that collectives take virtually no management responsibility for private tubewells; instead, this responsibility rests with individual farmers. In addition, the role of the collective in tubewell management has also declined over the past ten years (Table 2). Village leaders are primarily responsible for all management activities for collective wells including tubewell and pump maintenance (78% and 66%, respectively) and water fee collection (68% – column 1, rows 5, 7 and 9). However, between 1995 and 2004, many of these collective tubewell management activities were devolved from village leaders to individual farmers either by being privatized or through contracting arrangements. For example, in the case of maintaining tubewells, from 1995 to 2004 the share of tubewells maintained by well contractors increased 8%, while the share of those maintained by individual farmers increased by 2% (columns 2 and 3, rows 5 and 6). The trend is similar for other activities.

Groundwater markets. As tubewells and the accompanying pumping equipment have come under the control of private individuals, access to groundwater for those farmers that do not own and operate their own wells has become a new issue. In fact, markets to transfer tubewell and pump services from those with access to those without have not always existed. In the 1970s and 1980s, when most wells were owned and operated by the collective, simple rules governed water allocations in almost all villages. Most of these rules were based on a system in which all individuals were provided with water in an equitable way. In some villages, the collective provided water free or at a subsidized rate. In the early

Table 2. Change of management responsibilities for collective tubewells in northern China's villages, 1995 and 2004.

	Share of tubewell numbers (%)			
	Village leaders	Well contractors	Individual farmers	Sum (%)
Opening the gate				
1995	63	17	21	100
2004	51	27	23	100
Coordinating irrigation orders				
1995	66	16	19	100
2004	55	26	18	100
Maintaining tubewell				
1995	78	10	13	100
2004	67	18	15	100
Maintaining pump				
1995	66	13	21	100
2004	51	23	26	100
Collecting water fee				
1995	68	17	15	100
2004	57	28	16	100

Data source: authors' survey in 2004 (NCWRS dataset).

period after reform, however, traditional institutions began to breakdown (see Wang *et al.*, 2005). In today's world in which some, but not all, farmers own their own wells, new institutions have developed to transfer water from those with wells to those without.

In response to demand for water in an environment increasingly dominated by private and privatized wells, groundwater markets have begun to emerge in recent years as a way for many producers in rural China to gain access1to groundwater (Zhang *et al.*, 2005). This emergence, while new in China, in fact, appears to be following a pattern similar to that observed in parts of South Asia (Shah, 1993). In the 1980s groundwater markets were almost nonexistent in China and, even by the mid-1990s, according to the NCWRS data, only a small share of villages (21%) had groundwater markets. By 2004, however, tubewell operators in 44% of villages were selling water. Across all villages about 15% of private tubewell owners sold water. Although groundwater markets exist in less than half of northern China's villages, the numbers are still significant: we estimate that farmers in more than 100,000 villages are accessing water through groundwater markets. Moreover, in villages that have groundwater markets, these markets play an important role in transferring large volumes of water to a large share of households.

Farmers' response to increasing water prices

As the water table falls, the prices charged in groundwater markets increase. For instance, as per the CWIM data, when the water table in our Hebei villages declined from 4.4 m to 77.5 m, the price of groundwater for wheat producing households increased from 0.08 Yuan/m^3 to 0.56 Yuan/m^3 (Table 3). Since pumping costs rise as the water table declines, this indicates that, to some extent, groundwater prices, in fact, reflect the scarcity value of water resources. Across our CWIM sample of Hebei wheat producers, we estimate that pumping costs rise by 0.005 Yuan per cubic meter of groundwater extracted for each additional meter in pumping.

More importantly, as groundwater prices rise and water becomes scarce, farmers respond by reducing water use. Analysis of the behavior of Hebei wheat farmers in the CWIM data set indicates that, when groundwater price increased from 0.08 Yuan/m^3 to 0.56 Yuan/m^3, water use per hectare decreased from 6433 m^3 to 2154 m^3 (Table 3). Such a finding implies that, faced with increasing water scarcity, farmers respond to water price increases by decreasing the volume of water that they use. Data are not available to estimate the degree to which reduced groundwater use reflected higher crop water use efficiency versus lower crop production. However, evidence suggests that at least some of the reduced application is a reflection of gains in water use efficiency. If so, water pricing may be an effective policy instrument

Table 3. Groundwater prices under the various depth of water tables of Hebei wheat-producing households, 2004.

Share of samples (%)	Water table (m)	Groundwater price (Yuan/m^3) (average cost of groundwater)	Volume of water use per unit of land (m^3/ha)
1–25	4.4	0.08	6,433
26–50	6.7	0.20	5,285
51–75	24.6	0.30	2,934
76–100	77.5	0.56	2,154

Data source: authors' survey in 2004 (CWIM dataset).

to resolving water scarcity problems. Further supporting this contention is the fact that farmers' responses to rising prices in groundwater markets are not only in terms of reducing water use but also in terms of raising the use value of water by reallocating water from low to high value crops. Based on the analysis of our CWIM data for the Hebei region, we found that, as water tables fall, there has been an increase in the share of cash crops (such as horticultural crops, cotton and peanuts) (Table 4). That is, when the depth to water table increases from 4.7 to 79 m, the area share of cash crops increases from 13 to 41%. This implies that, as water tables fall, water becomes scarcer, and costs of acquisition rise, farmers not only consider how much water to use, but also how much value can be produced by water use. When water becomes the scarce factor of production, farmers try to maximize the output per unit of the water and increase water productivity.

However, despite potential resource conservation benefits, the rise of water prices (or costs to farmers for acquisition of self-pumped water) will have an inevitable negative impact on farmers. In other work that we have undertaken using the same data set, we estimate that doubling the price of groundwater in Hebei causes 75% of wheat producing farmers to lose money on cropping activities and has a negative effect on agricultural output (Huang *et al.*, 2006). Therefore, given the government's interest in maintaining rural incomes, any use of pricing policy almost certainly must also be accompanied by complementary policies that can offset the negative effect of price increases. In China today, this is feasible. For example, instead of a grain subsidy, China should consider giving a "decoupled water-price reimbursement payment" or "unconditional payment" to farmers. However, any such policy would of course have governmental budget implications. Water pricing can save water, but only with other costs.

Household and village adoption of water saving technology

Another possible response to water shortage is the adoption of water saving technologies. The survey covered three sets of water saving technologies: traditional technologies (agronomic-based, highly divisible; generally practiced by farmers in pre-People's Republic of China), household-based technologies (highly divisible; low fixed cost; requiring little collective action) and community-based technologies (requiring collective action for adoption and maintenance; high fixed costs). The adoption paths of these three different water saving technology types trace three distinct sets of contours. Moreover, the general path of each technology within each major category – traditional, household-based and community-based – tends to follow the trajectory of the other similar technologies within its category. In this subsection, we track adoption with a village-based measure of adoption in which a village is considered to have adopted a technology if at least one plot or farmer in the village uses the technology.

As the name implies, traditional water saving technologies have been used for many years, according to our data (Table 5). The strongest distinguishing characteristic of traditional water saving technologies is that, even as of the early 1950s, they were being used in a relatively large share of China's villages. For example, in 1950 farmers in 53% of northern China's villages were

Table 4. Relationship between groundwater table and share of high value crops.

Groundwater table (m)	4.7	8.8	40	79
Share of high value crop in total sown area (%)	12.8	15	22.4	40.6

Data source: authors' survey in 2004 (CWIM dataset).

Table 5. Share of villages adopting water saving technologies over time in northern China's villages, 2004.

	Traditional water saving technologies			Community-based water saving technologies		Household-based water saving technologies			
	Border	Furrow	Leveling	Ground pipe	Lined canal	Surface pipe	Plastic film	Retain stubble/low till	Drought resistant variety
1950	43	8	53	0	0	1	2	9	4
1955	43	9	54	0	0	1	2	9	4
1960	47	9	58	0	0	1	2	9	5
1965	48	10	60	0	1	1	2	9	5
1970	51	11	63	0	2	1	2	10	6
1975	52	13	64	1	3	1	2	11	6
1980	54	13	67	1	8	2	5	11	8
1985	55	14	72	2	9	10	11	16	16
1990	56	14	72	6	11	17	22	19	19
1995	58	15	73	12	17	23	33	28	25
2000	60	18	75	18	20	42	54	40	37
2004	61	18	76	24	24	47	58	53	42

Data sources: authors' survey in 2004 (NCWRS data set).

already leveling their land. During the reform period, the adoption of traditional technologies grew slowly, in part because traditional technology adoption rates were already high in the pre-reform and early reform era.

In contrast, household-based technologies followed a different technological adoption path over the past half-century (Table 5). Although it is difficult to distinguish exact levels of adoption, household-based water saving technology adoption rates were all low in 1950, ranging from 1% (surface pipe) to 9% (retain stubble/low till). Unsurprisingly, due to the relative abundance of water and the nature of farming at the time (collective-based with few incentives to maximize profits), household-based technology adoption rates at the village level remained low over the next 30 to 40 years. It was not until the early 1990s that their adoption rates soared. By 2004, farmers in at least 42% of villages were using each type of household-based water saving technology.

Finally, although the basic pattern of community-based technology adoption follows the same fundamental trend as household-level technologies, these paths start lower and rise at a slower rate (Table 5). Between the 1950s and 1980s, like household-level technologies, adoption rates were low. By the beginning of the reforms in the mid-1980s, the highest village-level adoption rate of a community technology (lined canals) was only 9%; on average, the level of adoption of community technologies during the mid-1980s was around 5%. By 2004, the rate of adoption rose relative to previous years, but lagged behind the adoption of household-based technologies. By 2004 the village-based measures show that, on average, only about 24% of communities had adopted community technologies.

While, based on these descriptive contours, it is unclear what is driving the adoption path of community-based technologies, work by Blanke *et al.* (2006) suggests that it is likely that there are two sets of forces that are at once encouraging and holding back adoption. On the one hand, rising scarcity of water resources is almost certainly pushing up demand for community-based technologies. On the other hand, the predominance of household farming in China (Rozelle & Swinnen, 2004) and the weakening of the collective's financial resources and management authority (Lin, 1991) has made it more difficult to gather the resources and coordinate the effort needed to adopt technologies that have high fixed costs and involve many households in the community. In contrast, household-based technologies may be more widely adopted due to relatively low fixed costs, divisibility, and minimal coordination requirements.

Conclusions and implications

The primary goal of this paper was to sketch a general picture of China's groundwater water resources with particular reference to agriculture and focusing on government polices and institutional issues. Our findings show that groundwater resources in northern China are heterogeneous across space and changing rapidly over time. While there are serious groundwater problems, including severe and growing groundwater overdraft in some areas of northern China (in around 10% of villages, the water table fell by more than 1.5 m per year), in many other areas – indeed, in more than half of northern China's villages using groundwater for agriculture – groundwater resources have not diminished at all or have not diminished very much over the past decade. There are serious problems, but these problems do not exist everywhere. Policies to address groundwater problems should therefore be carefully targeted.

Even with careful targeting, however, formal policies to confront groundwater problems will not be easy to implement. Government officials have done little to control the extraction of groundwater for agricultural uses or to protect its quality, despite the existence of many formal laws and regulations, even in those places facing serious problems. In contrast, farmers have been responsive to changing groundwater conditions – though in some cases their responses have added to the problem. Individual farmers (i.e. the private sector) have taken control of most well and pump assets; farmers are also increasingly taking responsibility for transferring water from those that have wells to those that demand water. And as the groundwater table falls and pumping costs rise, farmers respond by reducing water use, changing cropping patterns and adopting new water saving technologies. However, rising costs are currently a result of resource depletion rather than an instrument in its control. Furthermore, costs still do not reflect the full value of water but rather only its acquisition costs. If the problem is left to market forces, groundwater in many areas will continue to drop below "optimal" levels and many farmers, in particular the poorest, will ultimately be hurt.

The policy implication of our results is clear. A multi-step response by officials is required. First, they need to determine where serious overdraft is occurring and then focus attention on those areas with the most severe problems. In some of these areas the simple fact may be that agricultural groundwater use must be reduced. The question is if this will occur by default because pumping depths make further use uneconomic or, preferably, through more pro-active policies which help to ensure higher productivity per unit of water consumed and reduce pumping depths and hence energy costs. It is clear that, with proper incentives, farmers will respond by saving water and transferring water resources from those that have to those that do not and from lower to higher value uses. Farmers will respond further if formulas can be designed to implement price-based policies or any other set of policies that make the water scarcity more evident.

The challenges for implementing such policy are two-fold. First, policies to influence agricultural groundwater use have been difficult to implement around the world and perhaps particularly in socio-ecological environments such as China's with large numbers of small users scattered across great distances. Nonetheless, unlike its South Asian neighbor India, China has shown some success in developing decentralized technical and institutional mechanisms for administering services analogous in some ways to groundwater, including rural electricity provision and surface irrigation delivery. Similar models could be considered for groundwater. Second, increasing the scarcity value of groundwater implies increased costs to users, an outcome which will disproportionately hurt the poor and goes against China's national policies to both reduce poverty and reduce the gap between rich and poor. Simultaneously addressing groundwater and poverty challenges will not only require technical and institutional changes in the way groundwater is governed, but also the political will and economic capital to ensure that larger social objectives are met.

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