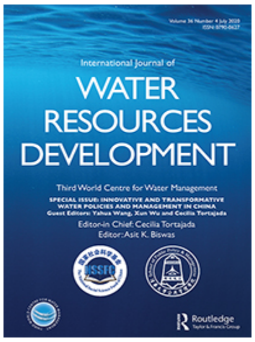

International Journal of Water Resources Development

ISSN: 0790-0627 (Print) 1360-0648 (Online) Journal homepage: https://www.tandfonline.com/loi/cijw20

Groundwater irrigation and management in northern China: status, trends, and challenges

Jinxia Wang, Yuting Jiang, Huimin Wang, Qiuqiong Huang & Hongbo Deng

To cite this article: Jinxia Wang, Yuting Jiang, Huimin Wang, Qiuqiong Huang & Hongbo Deng (2020) Groundwater irrigation and management in northern China: status, trends, and challenges, International Journal of Water Resources Development, 36:4, 670-696, DOI: 10.1080/07900627.2019.1584094

To link to this article: https://doi.org/10.1080/07900627.2019.1584094

Published online: 25 Mar 2019.

INTERNATIONAL JOURNAL OF WATER RESOURCES DEVELOPMENT
2020, VOL. 36, NO. 4, 670–696
https://doi.org/10.1080/07900627.2019.1584094

Groundwater irrigation and management in northern China: status, trends, and challenges

Jinxia Wang[a,b,*], Yuting Jiang[b,c], Huimin Wang[a], Qiuqiong Huang[d] and Hongbo Deng[b,c]

[a]China Center for Agricultural Policy, School of Advanced Agricultural Sciences, Peking University, Beijing, China; [b]Institute of Geographical Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing, China; [c]University of Chinese Academy of Sciences, Beijing, China; [d]Department of Agricultural Economics and Agribusiness, University of Arkansas, Fayetteville, USA

ABSTRACT
This study uses panel data from the North China Water Resources Survey in 2004 and 2016 to update the status of groundwater. In the past two decades, groundwater irrigation has spread to more villages, but declining groundwater tables and deterioration in water quality have become more serious. Some policy measures (well-drilling permits, water quotas, water resources fees) have been implemented in an increasing number of villages, but they still only reached a small fraction of villages. Some of the responses by farmers to these challenges have accelerated groundwater extraction. Policy efforts are needed to improve the effectiveness of policy implementation and enhance sustainable groundwater use.

ARTICLE HISTORY
Received 18 January 2018
Accepted 12 February 2019

KEYWORDS
Groundwater irrigation; supply reliability; groundwater table; groundwater quality; policy instruments; farmer responses

Introduction

Groundwater irrigation has significantly contributed to agricultural production in northern China. Northern China includes north China (Huabei: Beijing and Tianjing Municipalities, as well as Hebei, Shanxi and Inner Mongolia Provinces), northeast China (Dongbei: Liaoning, Jiling and Heilongjiang Provinces), northwest China (Xibei: Shaanxi, Gansu, Qinghai, Ningxia and Xinjiang Provinces), and part of Henan Province. Before the 1950s, groundwater irrigation was almost non-existent in the region; however, by the 1970s, it accounted for 30% of irrigation (Wang, Huang, Rozelle, Huang, & Zhang, 2009); and in 2004, nearly 60%. With the spread of groundwater irrigation, the number of tubewells in northern China increased from nearly zero in the early 1950s to more than 7.6 million by 2013, which is more than 80% of all irrigation tubewells in the country (Ministry of Water Resources [MWR], 2013; Wang, Huang, Rozelle, Huang, & Blanke, 2007). In northern China, crop water use accounts for 70% of groundwater withdrawal in floodplains and more than 87% in piedmont regions (Hua, Moiwo, Yang, Han, & Yang, 2010). Grogan et al. (2014) estimated that without groundwater, the decline in northern China's crop production would cause as much as a 10% loss in national production.

At the same time, heavy reliance on groundwater irrigation has placed tremendous pressure on groundwater resources and resulted in several adverse environmental outcomes.

CONTACT Jinxia Wang jxwang.ccap@pku.edu.cn
*The work done by the first author at both affiliated institutions contributed equally to the study.

The overdraft area increased from 190,000 km^2 in 2011 to nearly 300,000 km^2 by 2016, almost 90% of which falls in northern China (National People's Congress Standing Committee [NPCSC], 2016). In the Hai River basin, the most water-short region in northern China, 91% of plain areas are classified as overdraft areas, and groundwater overdraft has reached more than 40 km^3 (Shen, 2015). A direct consequence of the heavy pumping is the rapid decline in groundwater levels. For example, between 1974 and 2000, the rate of decline in shallow aquifers in the Hai River basin was as high as 1 m/y (Qiu, 2010); during the same period, the rate of decline in deep aquifers exceeded 2 m/y (Wang et al., 2009). Groundwater overdraft has also significantly reduced stream flow and led to the drying-up of 40% of waterways and the disappearance of hundreds of lakes in the Hai River basin (Jiang, 2009). Other negative environmental outcomes include land subsidence, groundwater quality deterioration, and seawater intrusion (Aeschbach-Hertig & Gleeson, 2012; Guo, Zhang, Cheng, & Li, 2015; Wang, Li, Huang, Yan, & Sun, 2017a).

Achieving sustainable groundwater use while maintaining high-level food security is among the main challenges facing policy makers in China. However, policy makers are attempting to address a problem about which they are not fully informed. The disconnect between the reality of groundwater resources and policy making prevalent in many countries (Shah, 2008) arises because it is difficult to collect information on groundwater users, a large number of individual farmers spread out over large areas (Shen, 2015). It is also difficult to collect information on all aquifers, since their hydrogeological characteristics vary across space. But any sound policy making requires an understanding of the status of groundwater resources and how they are managed (Liu & Zheng, 2016). Thus, this study aims to inform policy makers and researchers about the groundwater sector in northern China. It has two key objectives: to provide an updated overview of groundwater irrigation development, the status of groundwater resources, and concurrent environmental issues in northern China; and to examine the actions taken by the government and farmers in response to increasing water scarcity.

This study uses field survey data from 2015 and panel data for the past two decades (2004–2015),[1] in contrast to most studies, which rely on cross-sectional data and present insights applicable to a decade ago. For example, Wang et al. (2007, 2009) focused on groundwater problems, particularly the government's and farmers' responses to increasing water scarcity. While these studies used data from field surveys administered in 2004, they did not identify the latest development of groundwater irrigation. Thus, this research can be considered as updating that past work. In the dynamic policy environment of China, it is important to update policy analyses using the most recent data. For example, several national policies and regulations have recently been issued that could significantly impact groundwater management (Wang et al., 2017a). One is the 'Three Red Lines', issued in 2011, which established clear targets for reductions in water withdrawal rates and improving irrigation efficiencies. According to the policy, by 2030, total water withdrawal in China should be below 700 km^3; irrigation efficiency should be increased to 60% and water withdrawal should be less than 40 m^3 per RMB 10,000 of industrial added value; and the proportion of water function zones complying with the water quality standard should be above 95% (State Council, 2012). This policy has increased the prevalence of policy instruments used to improve groundwater management (e.g. permit policy for well drilling, well-spacing policy, quota management and water resources fees), and the analysis of this study reflects the latest policies.

The study also contributes to the broader literature and generates implications for groundwater management in other countries. A novel aspect of the present study is that most of the analysis is conducted at the village level, where groundwater management actually takes place. Most studies of groundwater management are conducted at the macro level, probably because information at the village level is not readily available (e.g. Cao, Cheng, & Li, 2009; Li et al., 2015; Liu & Zheng, 2016; Shen, 2015). Foster, Chilton, Cardy, and Schiffler (2000) argued that the main challenge in groundwater management is how to link micro-level users to macro-level aquifer management effectively. Liu and Zheng (2016) also suggested that the improvement of groundwater management requires more involvement by stakeholders (e.g. farmers, well operators, water officials) in addition to legislative improvements. In rural China, villages and individual farmers have de facto rights to groundwater through their ownership of or access to tubewells. The present study finds that it is imperative that all policy planning related to groundwater management consider the potential impact on farmers and their reaction to the proposed policies. Shah (2008) argued that issuing a national water policy and groundwater law may be useless for groundwater management unless the policy measures are effectively implemented at the national and local levels. This study examines the extent to which some of the major groundwater policies are implemented.

The remainder of this paper is organized as follows. The following section describes the datasets that form the basis of this study. We then describe the changes in groundwater irrigation and supply reliability in northern China and discuss the increasing challenges, the adverse effects on the quantity and quality of groundwater resources, and the major environmental problems that can be attributed to groundwater irrigation. Finally, we examine policy measures to manage groundwater and farmers' response to changes in groundwater resources.

Data

We use 2004 and 2016 data from the North China Water Resource Survey (NCWRS). In 2004, the NCWRS interviewed village leaders from 400 villages across 50 counties in six provinces in northern China (Wang et al., 2009) (Figure 1). To ensure correct data collection, the researchers invited at least two village leaders with rich experience to participate in the interviews. The sample areas cover three major river basins: Hai River (Hebei Province), Yellow River (Inner Mongolia, Henan, Shaanxi and Shanxi Provinces), and Liao River (Liaoning Province) – all six of these provinces are major agricultural production regions. In 2016, one village was excluded from the sample because it had merged with other villages. The 2004 survey collected information for 1995 and 2004, and the 2016 survey did so for 2015. This empirical analysis uses information for 399 villages for 1995, 2004 and 2015. The scope of the surveys was rather broad and included more than 10 sections. Although the survey gathered data on surface water and groundwater resources, this analysis focuses on groundwater.

To generate a sample representative of northern China, the survey used stratified random sampling (Wang et al., 2009). First, the counties in each province were categorized into four groups on the basis of water scarcity: very scarce, somewhat scarce, normal, and mountain/desert.[2] Then, two or three counties were randomly selected from each category. The number of sample counties varied, since the total number of

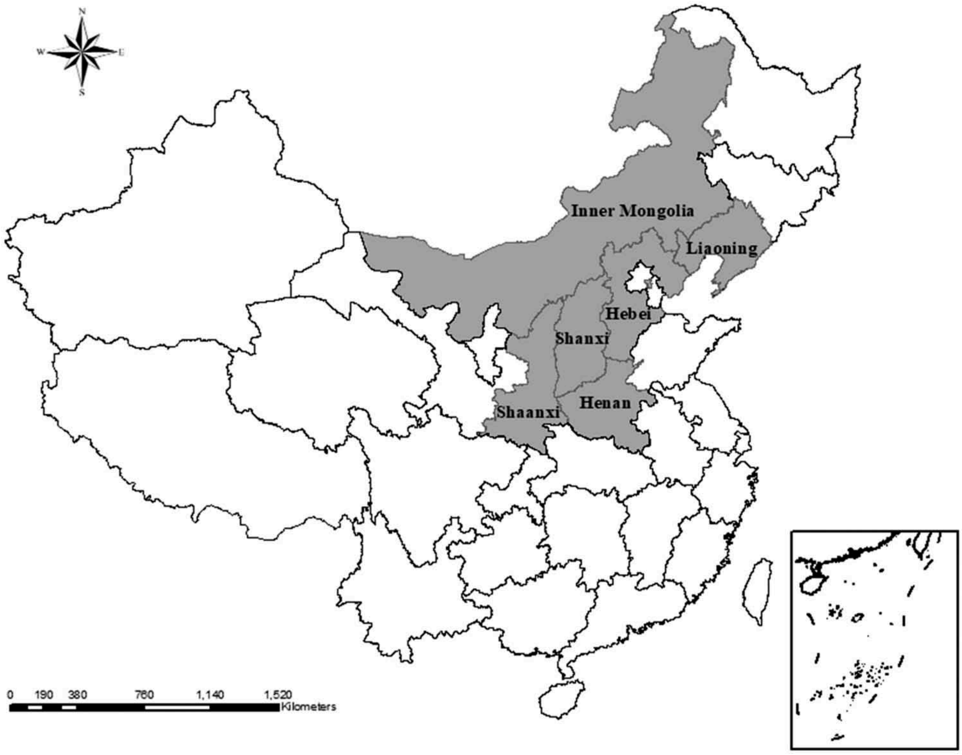

Figure 1. Sample provinces.

counties in each category differed. Second, two townships were randomly selected from each county. Finally, four villages were randomly selected from each township. All the data analyses used a set of population-based weights.

Development of groundwater irrigation and its supply reliability in northern China

Development of groundwater irrigation

Over the past 20 years, groundwater irrigation has continued to spread to more villages, from 57% in 1995 to 66% in 2015 (Table 1). Among those villages that began groundwater irrigation in 1995 (9%), 3.7% converted from rainfed agriculture to groundwater-irrigated agriculture, and 3.4% switched from surface water irrigation to conjunctive irrigation using both surface water and groundwater. For the remaining 1.9%, surface water irrigation was no longer available, and these villages had to resort to groundwater irrigation. The number of groundwater-irrigated areas exhibiting a similar growing trend increased from 49% in 1995 to 67% in 2015.

Although groundwater has become more important for agricultural production in northern China, it still varies significantly by region. For example, in Hebei Province, more than 90% of the sample villages used groundwater irrigation in both years. By contrast, this share

Table 1. Development of groundwater irrigation.

	Villages with groundwater irrigation (%)	Groundwater-irrigated area (%)
Northern China		
1995	57	49
2004	63	55
2015	66	67
Henan		
1995	59	77
2004	61	88
2015	60	93
Hebei		
1995	91	94
2004	93	92
2015	91	90
Shaanxi		
1995	40	59
2004	36	49
2015	42	35
Shanxi		
1995	58	55
2004	62	66
2015	63	74
Liaoning		
1995	38	32
2004	64	47
2015	57	46
Inner Mongolia		
1995	63	35
2004	74	43
2015	81	69

Source: Authors' survey in 2004 and 2016 (North China Water Resource Survey data-set).

in Shaanxi Province lingered at about 40% over the studied period. Similar spatial variations are observed for the share of groundwater-irrigated areas.

During 2004–2015, the growth rate of the village coverage of groundwater irrigation declined, while the expansion of groundwater-irrigated areas accelerated. The share of villages using groundwater irrigation increased by 3 percentage points during this period, with half of the increment during 1995–2004 (6 percentage points, Table 1). By contrast, during the more recent decade, the share of groundwater-irrigated areas increased by 12 percentage points, 6 percentage points more than in the previous decade. These results imply that while it is impossible for all villages to explore groundwater for irrigation, in the villages that do so, the importance of groundwater has increased markedly. For example, in Henan Province, although only 59% of its villages used groundwater irrigation in 2015, as much as 93% of the area was irrigated by groundwater. Indeed, among the 55 sample villages in Henan Province, 31 depended on groundwater for irrigation, and 5 on surface water; one used both groundwater and surface water, and 18 practised rainfed agriculture.

The growth rate of groundwater irrigation development also varies by province. In the past two decades, two provinces have experienced rapid development in the village expansion of groundwater irrigation. In Liaoning Province, the share of villages using groundwater irrigation increased from 38% in 1995 to 57% in 2015. In Inner Mongolia, the share increased from 63% to 81%. By contrast, the shares either stayed the same or showed modest growth in the other sample provinces. Similar to the trends observed for the share of villages with groundwater irrigation, that of areas irrigated by groundwater increased more rapidly in Inner Mongolia (35 percentage points in the past two decades) than in Henan, Shanxi, and Liaoning Provinces. Hebei and Shaanxi Provinces, on the contrary, witnessed a decline in the share of areas irrigated by groundwater. The drop in Shaanxi Province was particularly large, with a decline from 59% in 1995 to 35% in 2015 (24 percentage points). Currently, most discussions on groundwater policies and management to address groundwater overdraft and water scarcity focus on the Hai River basin and provinces downstream of the Yellow River basin. However, the descriptive evidence in this study clearly shows that attention is warranted in regions where groundwater irrigation is rapidly expanding, such as the Liao River basin. The learnings derived from the Hai River and Yellow River basins could then be applied to other regions, with modification.

Supply reliability of groundwater irrigation

An important consideration when assessing the expansion of groundwater irrigation is whether the expanded groundwater supply is reliable and how reliability changes over time. In the NCWRS, village leaders were asked the following question for three periods: 1993–1995, 2002–2004 and 2013–2015: 'In this period, was there any part of any year that farmers did not have access to sufficient quantities of groundwater and/or timely groundwater irrigation?' If a village leader answered yes, the groundwater irrigation supply in the village was considered unreliable. In the 2016 round of the NCWRS, the leaders were asked to report the percentage of sown area with reliable groundwater irrigation supply between 2013 and 2015. The answers to these questions were used to generate two indicators of the supply reliability of groundwater irrigation: share of villages and share of sown area.

Table 2 shows that groundwater irrigation does not necessarily provide highly reliable irrigation. Even in 1993–1995, only 68% of villages had reliable supplies of groundwater irrigation. The shares of sown areas show similar results. In 2013–2015, about 40% of crop-sown areas did not have a reliable supply of groundwater irrigation. Further, the supply became less reliable over time (Table 2). The share of villages with reliable supplies of groundwater irrigation dropped to 56% in 2002–2004, a decrease of 12 percentage points from 1993–1995. This share further dropped to 53% in 2013–2015. In other words, almost half of the villages in northern China do not have reliable groundwater irrigation supply. These findings indicate that although groundwater irrigation has been extended to more areas and accounts for a larger share of agricultural water supply (Table 1), the benefits of such an expansion are discounted by declining supply reliability. This should be factored into any consideration of the further expansion of groundwater irrigation, and at the very least, changes in the supply reliability of groundwater irrigation should be recorded.

In the NCWRS, village leaders were also asked to list the major causes of unreliable groundwater supply. For all three periods, about 80% cited a sinking groundwater table as a major reason, followed by low levels of precipitation or drought, which was reported by 11% of leaders for 2002–2004 and 15% for 1993–1995 and 2013–2015. This is probably because groundwater in shallow aquifers is refilled by rainfall or stream runoff. In these areas, fluctuations in precipitation lead to changes in the groundwater table, which then

Table 2. Supply reliability of groundwater irrigation (as reported by village leaders).

	Villages having reliable groundwater irrigation (%)	Crop-sown area with reliable groundwater irrigation (%)
Northern China		
1993–1995	68	-
2002–2004	56	-
2013–2015	53	60
Henan		
1993–1995	66	-
2002–2004	53	-
2013–2015	30	60
Hebei		
1993–1995	76	-
2002–2004	62	-
2013–2015	53	51
Shaanxi		
1993–1995	50	-
2002–2004	31	-
2013–2015	61	45
Shanxi		
1993–1995	79	-
2002–2004	67	-
2013–2015	56	62
Liaoning		
1993–1995	51	-
2002–2004	52	-
2013–2015	72	70
Inner Mongolia		
1993–1995	79	-
2002–2004	48	-
2013–2015	47	67

Source: Authors' survey in 2004 and 2016 (North China Water Resource Survey data-set).
Note: '-' means no data.

cause variations in the reliability of groundwater supply. The third-most commonly reported reason is the poor maintenance and operation of tubewells. However, the share of villages that listed this as a major reason fell from 10% in 1993–1995 to 1% in 2013–2015. Thus, it appears that the top two reasons for unreliable groundwater irrigation are related to the sinking groundwater table, an important indicator of increasing water scarcity (Wang et al., 2009). In addition to shrinking quantities of groundwater in the aquifer, the findings reveal additional challenges brought about by increasing water scarcity, namely less reliable groundwater supply, which has slowed agricultural production.

The by-province results show that the reliability of groundwater supply is declining in four of the six sample provinces (Table 2), an alarming rate. Between 1993–1995 and 2013–2015, the share of villages with reliable groundwater supply fell by 23 percentage points in Hebei and Shaanxi, 32 in Inner Mongolia, and 36 in Henan. The supply reliability of groundwater irrigation dropped to less than 50% in Inner Mongolia and 30% in Henan. For 2013–2015, the shares of crops sown with a reliable supply of groundwater irrigation were near or less than 50% in Hebei and Shaanxi. Immediate policy attention is thus needed in these provinces to address irrigation reliability. By contrast, in Liaoning Province, the share of villages with a reliable supply of groundwater irrigation increased across the sample years. In addition, the share of crop-sown areas with a reliable supply of groundwater was as high as 70% in 2013–2015.

Challenges in groundwater resources

Decline in the groundwater table

The survey results show that most villages in northern China have experienced a decline in their groundwater table (Table 3). In 1995–2004, the groundwater table sank in 64% of the sample villages, and this share increased to 75% between 2005 and 2015. In addition to the greater number of villages, the rate of decline in the groundwater table has become more serious. In 1995–2004, the groundwater table dropped by 0.25 m annually in 17% of the sample villages. In 39%, the annual decline was 0.25–1.5 m. In this period, the percentage of villages whose groundwater table sank by more than 1.5 m was only 8%. The MWR classifies groundwater as 'seriously over-exploited' in areas where the groundwater table sinks by more than 1.5 m annually. Hence, in 1995–2004, groundwater in 8% of villages in northern China was seriously overexploited (or experienced groundwater overdraft). And in 2005–2015, this increased to 34%.

Most provinces faced a similar situation. In the past 20 years, the share of villages experiencing a sinking groundwater table increased in four provinces (Henan, Shanxi, Liaoning, Inner Mongolia). The increment ranged from 7 percentage points (Inner Mongolia) to 24 percentage points (Henan). In Hebei and Shaanxi Provinces, these shares decreased, with the drop more pronounced in Shaanxi Province (11-percentage-point decline). Although the share of villages that experienced a sinking groundwater table show mixed trends across provinces, investigation of the share of villages with groundwater overdraft problems showed consistent patterns. In the past 20 years, in all six provinces, this share has significantly increased. The increments are small in Henan

Table 3. Decline in the groundwater table across the two periods (as reported by village leaders).

		Villages (%) with an annual rate of groundwater decline of:		
	Villages with sinking groundwater table (%)	< 0.25 m	0.25–1.5 m	> 1.5 m
Northern China				
1995–2004	64	17	39	8
2005–2015	75	10	31	34
Henan				
1995–2004	61	19	36	6
2005–2015	85	24	50	11
Hebei				
1995–2004	88	8	64	16
2005–2015	85	6	25	54
Shaanxi				
1995–2004	74	4	56	14
2005–2015	63	0	19	44
Shanxi				
1995–2004	64	14	34	16
2005–2015	79	5	35	39
Liaoning				
1995–2004	52	31	21	0
2005–2015	67	25	38	4
Inner Mongolia				
1995–2004	64	32	25	7
2005–2015	71	5	23	43

Source: Authors' survey in 2004 and 2016 (North China Water Resource Survey data-set).
Note: The samples for this table include villages using groundwater irrigation.

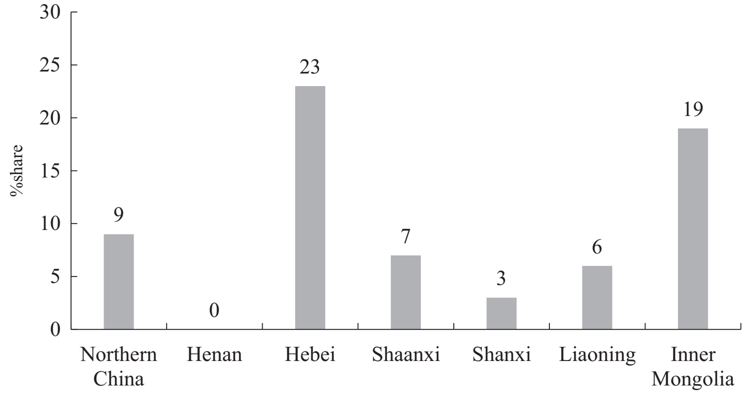

Figure 2. Share of villages with groundwater overdraft (as reported by village leaders).
Source: Authors' survey in 2004 and 2016 (North China Water Resource Survey data-set).

and Liaoning Provinces (around 4 percentage points) but more than 20 percentage points in Shanxi Province and 30 percentage points or more in Shaanxi, Hebei, and Inner Mongolia Provinces.

The survey results also revealed inconsistencies in the assessment of groundwater overdraft between the perception of village leaders and that reflected by the rate of decline for the groundwater table. The survey asked village leaders whether groundwater overdraft occurred in their villages, in response to which only 9% said yes (Figure 2). This share is considerably lower than that of villages whose groundwater table drops more than 1.5 m annually (Table 3). This inconsistency is observed for all provinces (Figure 2, Table 3) and may be attributed to the limited knowledge of groundwater overdraft among water users in rural villages. Indeed, during the NCWRS, when village leaders were asked whether they were aware of the phenomenon of groundwater overdraft, only 22% answered yes. Therefore, it is not surprising that village leaders did not consider the groundwater in their villages to be overexploited, even when the groundwater table dropped by more than 1.5 m/y.

To further assess water users' knowledge of groundwater overdraft, village leaders who believed that groundwater overdraft occurred in their villages were asked to list the resulting environmental issues. About 58% reported environmental issues (Table 4). Among these respondents, 44% believed that the primary environmental issue was the fall in the groundwater table. Deterioration in groundwater quality (8%) and land desertification (6%) were listed as other negative environmental effects of groundwater overdraft.

Deterioration in groundwater quality

Village leaders' responses indicate that groundwater quality has deteriorated in northern China (Table 5). In 2004, nearly 60% considered the quality of groundwater good. However, in 2015, this share dropped to 39%, a decrease of 21 percentage points. In other words, the share of village leaders who rated the groundwater not good (average or poor) increased from 40% in 1995 to 61% in 2015. Farmers' perception of the deterioration in groundwater quality is consistent with the government's monitoring data. Based on the monitoring data of the MWR for 778 tubewells in 2006, groundwater

Table 4. Environmental issues due to groundwater overdraft (as reported by village leaders, 2016).

	Villages with environmental problems (%)	Environmental problems (% of villages)		
		Sinking groundwater table	Groundwater pollution	Desertification of land
Northern China	58	44	8	6
Henan	0	-	-	-
Hebei	54	38	16	0
Shaanxi	40	40	0	0
Shanxi	50	50	0	0
Liaoning	50	25	25	0
Inner Mongolia	85	54	15	16

Source: Authors' survey in 2016 (North China Water Resource Survey data-set).
Note: '–' denotes no data.

Table 5. Groundwater quality over time (as reported by village leaders).

	Villages (%) that rated groundwater quality as:		
	Good	Average	Poor
Northern China			
1995	60	24	16
2004	59	23	18
2015	39	36	25
Henan			
1995	41	35	24
2004	45	35	20
2015	26	52	22
Hebei			
1995	50	30	20
2004	48	32	20
2015	25	53	22
Shaanxi			
1995	52	39	9
2004	52	34	14
2015	48	22	30
Shanxi			
1995	77	12	11
2004	77	11	12
2015	38	26	36
Liaoning			
1995	65	21	14
2004	66	19	15
2015	38	40	22
Inner Mongolia			
1995	66	17	17
2004	65	17	18
2015	56	25	19

Source: Authors' survey in 2004 and 2016 (North China Water Resource Survey data-set).
Note: Village leaders' response on groundwater quality is based on their experience in their villages. 'Average' means that the quality is what they thought is commonly accepted by farmers and reflected the overall average level of groundwater quality in their villages. 'Good' means better than 'average', and 'poor' means worse than 'average'.

in 61% was polluted and unsuitable for drinking. In 2015, the number of monitored tubewells had grown to 2013, and 80% had polluted groundwater. Therefore, the deterioration in groundwater quality is more serious based on government monitoring data than farmers' perception. This implies that the government is better positioned to provide information to farmers to take measures to avoid damage due to poor groundwater quality.

A shrinking share of villages with good groundwater quality and an increasing share of villages with bad groundwater quality are observed in all sample provinces. Good groundwater quality was reported in fewer than 30% of the sample villages in Henan and Hebei Provinces. The share of villages reporting good groundwater quality declined by 39 percentage points in Shanxi Province, the largest decrease among all provinces. The share of villages that reported poor groundwater quality in Shanxi Province reached 36%, which is also the highest among all the sample provinces. Shaanxi Province also experienced a considerable increase in the share of villages reporting poor groundwater quality, from 9% in 1995 to 30% in 2015.

A wide range of factors causing poor groundwater quality has been reported (Table 6). Nearly half the village leaders blamed natural causes. However, human-induced factors have also been reported. Anthropogenic causes include industrial wastewater pollution, domestic wastewater pollution, and agricultural activities. Industrial pollution was most frequently cited as the cause of deteriorating groundwater quality by village leaders (36%). Agricultural activities (both crop and livestock production) were listed by 28% of villages. Over time, a greater number of villages reported both sources. The share of villages listing fertilizer and pesticide pollution increased from 2% in 1995 to 18% in 2015, and that of villages citing

Table 6. Causes of poor groundwater quality (as reported by village leaders).

	Villages (%) that reported this reason:					
	Natural causes	Industrial wastewater pollution	Domestic wastewater pollution	Livestock wastewater pollution	Fertilizer and pesticide pollution	Saline water infiltration
Northern China						
1995	56	29	0	0	2	9
2004	50	34	0	0	4	7
2015	48	36	14	10	18	5
Henan						
1995	36	63	0	0	18	0
2004	33	67	0	0	22	0
2015	18	27	18	27	46	0
Hebei						
1995	45	27	0	0	0	45
2004	55	18	0	0	0	45
2015	0	73	36	9	27	0
Shaanxi						
1995	50	17	0	0	33	0
2004	55	0	0	0	0	0
2015	50	25	25	13	13	13
Shanxi						
1995	56	33	0	0	0	0
2004	67	33	0	0	0	0
2015	77	32	5	0	5	0
Liaoning						
1995	66	33	0	0	0	0
2004	67	33	0	0	0	0
2015	43	43	14	14	21	0
Inner Mongolia						
1995	66	8	0	0	17	8
2004	75	8	0	0	17	8
2015	73	36	0	0	0	18

Source: Authors' survey in 2004 and 2016 (North China Water Resource Survey data-set).

livestock wastewater pollution grew from 0% in 1995 and 2004 to 10% in 2015. These numbers demonstrate that the negative impacts of agricultural activities on groundwater quality have become increasingly notable over time. Domestic waste and salinization were also reported as contributing to the deterioration in groundwater quality. No village leader listed livestock wastewater and domestic waste until 2015.

In most sample provinces, a significant share of village leaders (more than 20%) reported industrial wastewater pollution as a cause of deteriorating groundwater quality. The influence of industrial wastewater pollution is more extensive in certain provinces; for example, 73% of the sample villages in Hebei Province listed it as a cause. Moreover, the share of villages affected by industrial wastewater pollution continued to grow between 1995 and 2015, with Henan Province as an exception. Although livestock wastewater and domestic wastewater pollution only emerged after 2004 as causes of poor groundwater quality, they have already become the main forces leading to poor groundwater quality in some provinces. In Henan Province, 27% of village leaders reported livestock wastewater pollution as a cause of poor groundwater quality, and 18% reported domestic wastewater pollution. Saline water infiltration was a serious problem in Hebei Province before 2004, although no village leader listed it as a cause in the 2015 survey. By contrast, a greater number of villages in Inner Mongolia have experienced saline water infiltration in the past decade.

Policy measures and farmers' response to groundwater challenges

Policy measures for groundwater management

Owing to neglect over time, China lacks distinct groundwater management systems, and groundwater has been separately managed by various agencies (Shen, 2015; Wang et al., 2009). Since 1998, the MWR has had the administrative power to manage water resources (including groundwater) in China, while the Ministry of Housing and Urban-Rural Development is responsible for urban groundwater management, the Ministry of Environmental Protection is responsible for groundwater quality management, and the China Geological Survey under the Ministry of Land and Resources (MLR) is responsible for groundwater monitoring and information collection. How to share the groundwater information of this latter ministry remains a major barrier to integrated groundwater management, and the MWR has set up its own groundwater monitoring stations in recent years. Also, there are far fewer officials working in the groundwater division than in other divisions (e.g. flood control and surface water system management). Therefore, it is no surprise to find a lack of national legislation focusing on groundwater management, and groundwater management has generally followed the similar management framework of surface water resources. For example, according to the 2002 Water Law, the control of water withdrawal and quota management have been applied to both surface and groundwater management (National People's Congress Standing Committee [NPCSC], 2002). The Water Law also specifies that water ownership belongs to the state, similar to both surface and groundwater resources.

Beyond formal legislation, central and local governments have launched policy measures to manage groundwater resources. At the national level, one of the major regulations is to establish a water withdrawal permit system and a water resources fee (State Council, 2006). This regulation applies to both surface and groundwater resources. Water quota management is another national policy pushed by the central government and applied to both surface and groundwater resources. National regulations have also established a groundwater function zoning system (Shen, 2015). National guidance on the groundwater function zone was issued by the MWR in 2005 and the MLR in 2006. In 2012, the MWR issued a technical guideline on groundwater overdraft zone assessment.

Some local governments have specific groundwater management legislation, particularly in northern China (e.g. Shanxi Province in 1982 and the other four provinces except Henan after 2013). In Henan Province, draft local groundwater management legislation has been in the discussion stage since 2014. However, local legislation may not provide effective solutions to groundwater problems. The field survey and communication with local officials found two major local regulations for managing rural groundwater: a well-drilling permit system and a well-spacing policy. In some provinces (e.g. Shanxi and Inner Mongolia), these two policies are regulated by provincial water resources bureaus. However, in the other four sample provinces, no formal regulations have been issued. That is, in most cases, these two local regulations are implemented informally, depending on local officials' efforts and consideration. Besides these two kinds, no regulations are commonly implemented in rural areas. Finally, similar to managing surface water resources, both national and local governments have invested in water-saving technologies (WST) in rural China.

Importantly, most regulations or policies are mainly suitable for managing urban or industry groundwater issues, not for rural groundwater issues. The first major reason is that increasing farmers' income means easing the farmers' burden, but the regulations or policies force farmers to increase input somewhat. The second major reason is the high implementation cost because of tubewell dispersion in rural areas. The third is the poor performance of groundwater measures. Therefore, to promote the implementation of groundwater regulations or policies, such as quota management and water resources fees, some local governments have encouraged farmers to install integrated circuit cards (IC cards) for tubewells, to measure groundwater withdrawal.

Since 2011, to achieve the Three Red Lines policy goal, the central and local governments have renewed efforts to effectively implement existing policies. For groundwater management, the first important policy goal (first red line) is to control the total groundwater withdrawal and prevent the decline of groundwater tables. The second important policy goal (second red line) is to improve irrigation efficiency. In the following discussion, we will mainly focus on policy measures that are achieving the goals, both of which focus on quality management. In summary, well-drilling permit systems, well-spacing policies and quota management are direct policies that can contribute to meeting the first Red Line, while installing IC cards, collecting a water resources fee, and extending WST can help achieve the second Red Line. The following section discusses these policies and provides empirical evidence on their implementation. Other policies that are not discussed in detail are at the macro planning level, and thus unobservable by farmers (such as groundwater function zone management and property rights reform), or do not show potential for implementation in rural areas (such as withdrawal permit systems). In rural China, a well-drilling permit system rather than a water-withdrawal permit system is implemented. And some policies, such as replacing groundwater irrigation with surface water resources, fallowing land, and adjusting the cropping pattern with subsidies to farmers, have only begun to be implemented in a few pilot project regions, such as Hebei Province. Thus, we do not discuss these policies in detail.

For controlling groundwater quality problems, no effective polices have been implemented, and policy makers have only begun to investigate the groundwater quality status. In the last two years, the central government in China is promoting zero increase in fertilizer and pesticide use. If this programme can be effectively implemented, it will be able to address groundwater quality deterioration.

According to Theesfeld (2010), groundwater management instruments generally fall into three groups. The first group includes regulatory instruments, well-drilling permit systems, well-spacing policies, and quota management. The second group includes economic instruments such as water resource fees. The third group includes voluntary or advisory policy instruments. An example is self-governance in groundwater management. This is discussed in the 'Farmers' Response to Increasing Groundwater Challenges' section. We discuss not only regulatory instruments but also economic instruments. Importantly, we also discuss technological instruments promoted by the government, IC cards, and WST. Some policy measures, such as groundwater function zone management, are implemented at provincial or river basin rather than village levels, so most village leaders and farmers are not familiar with them. Therefore, these policies are excluded from the discussion. Other policy measures, such as converting groundwater irrigation into surface water irrigation, fallowing land, and providing subsidies for crop mix changes, have only begun to be implemented in a few pilot project regions. They are not included in the discussion either.

Permit policy for well drilling

With the expansion of groundwater irrigation and the consequent decline in the groundwater table, controlling the number of tubewells is a priority. In the early 1990s, even without national regulations permitting well drilling, some provinces in northern China began to implement formal or informal well-drilling permit policies. These policies require that farmers obtain permission from local water resources bureaus before sinking tubewells. The emergence of this policy can also be attributed to the privatization of tubewells and that individual farmers have become important investors and managers in this technology (Wang et al., 2009; Wang, Xu, Huang, & Rozelle, 2006). The objective of this policy is to control farmers' behaviour in the digging of groundwater tubewells to realize the sustainable use of groundwater. Despite the policy being implemented in certain provinces as early as the 1990s, it was not included in the 2002 Water Law, and no national water regulation has addressed it. This may be the major reason for its implementation in the field. Shen (2015) pointed out that this policy is also inconsistent with the recent reform push to reduce administrative permits in China.

In the past two decades, local governments have accelerated the implementation of well-drilling permit policies, particularly in provinces with rapid expansion of groundwater irrigation. In 1995, 18% of villages had a well-drilling permit policy, and this number increased to 34% by 2004 (Table 7). From 2004 to 2015, it increased to 54%. The acceleration of policy implementation over the past decade was more remarkable in Liaoning and Inner Mongolia, with the number increasing from 18% to 55% in Liaoning and from 19% to 30% in Inner Mongolia. Table 1 previously showed that the expansion of groundwater irrigation in these two provinces is also higher than that of other provinces, suggesting that in regions with expanding groundwater irrigation, local

Table 7. Implementation of well-drilling permits and well-spacing requirements (as reported by village leaders).

	Villages with a well-drilling permit policy (%)	Villages with a requirement for well spacing (%)
Northern China		
1995	18	28
2004	34	44
2015	54	48
Henan		
1995	14	26
2004	16	32
2015	22	36
Hebei		
1995	4	25
2004	30	49
2015	35	40
Shaanxi		
1995	39	52
2004	58	65
2015	73	71
Shanxi		
1995	21	31
2004	38	50
2015	55	64
Liaoning		
1995	11	7
2004	19	17
2015	74	23
Inner Mongolia		
1995	20	27
2004	39	52
2015	61	56

Source: Authors' survey in 2004 and 2016 (North China Water Resource Survey data-set).

governments have realized the importance of controlling farmers' drilling of tubewells and are investing greater efforts to implement this policy.

Well-spacing policy

Like the well-drilling permit policy, well spacing has been implemented by local governments over the past two decades. Given the limited availability of groundwater resources in the same aquifer, failure to consider the layout of tubewells in the aquifer will affect the supply reliability of groundwater irrigation. Withdrawal from one tubewell will affect the groundwater availability of other tubewells in the same aquifer (Huang, Wang, Rozelle, Polasky, & Liu, 2013). Frija, Dhehibi, Chebil, and Villholth (2015) also stated that management tools such as appropriate well spacing are needed in areas with groundwater overexploitation and degradation. Therefore, a well-spacing policy to control farmers' tubewell investment is a crucial measure to ensure the supply reliability of groundwater irrigation. In 2010, the MOHURD issued its technical guidance on tubewell spacing in both rural and urban regions. However, owing to time-consuming and technical requirements for understanding the local hydrogeological conditions and providing scientific information for well spacing, the implementation of this policy mainly depends on local people's experience (e.g. county officials, drilling teams, farmers). This has hindered the implementation of well-spacing policies in the field.

Despite some improvement, the implementation has yet to cover most villages in northern China. In 1995, 28% of villages considered well spacing when they dug tubewells (Table 7). This number increased to 44% in 2004, rising by 16 percentage points. Although more villages began to implement this policy after 2004, the increment is only 4 percentage points, less than that in the previous decade. Despite the increase in the rate of implementation, in 2015, fewer than half of villages (48%) implemented this policy.

The by-province analysis reveals that the implementation of a well-spacing policy is no better in regions with higher dependence on groundwater. For example, the share of groundwater-irrigated areas in Hebei Province was more than 90% (Table 1), but fewer than half of the villages considered well spacing when digging tubewells (Table 7). In both Shaanxi and Shanxi Provinces, groundwater-irrigated areas were less than those in Hebei Province in 2015 (42% in Shaanxi and 63% in Shanxi). But the implementation rate for a well-spacing policy in these two provinces was better than that in Hebei: more than 60% (Shanxi) or 70% (Shaanxi) of their villages had such a policy in 2015.

Quota management

To meet the policy objective that total water withdrawal does not exceed 700 km^3 by 2030, the central government has prioritized the implementation of a water quota policy (Wang et al., 2017a). Quota management has been shown to be an effective means of resource management and has been applied at the national level. The reviews conducted by Molle (2009) showed that quota management is a more commonly used regulation mechanism than price-based policy instruments. Madani and Dinar (2013) found that quota management can outperform other common pool resource management regulation mechanisms, such as tax-based management, in terms of social welfare, social justice, and robustness.

Although water quota management was first introduced in China in the 2002 Water Law, it did not become a priority until the Three Red Line policies issued by the central government in 2012 (National People's Congress Standing Committee [NPCSC], 2002; State Council, 2012). According to the central government's requirement, river basin management authorities and local water resources bureaus should determine water quotas for various water users at different administrative levels (river basin, province, city, county, irrigation district, village). Under the water quota system, all water users should obtain withdrawal permission from upper-level water management authorities, and their withdrawal rates (both surface and groundwater) should not exceed their allocated quota.

Thus far, the implementation of such as policy has remained slow. Under the central government's guidance, many provinces have organized water experts to calculate water quotas at various levels. While certain provinces have calculated quotas at the river-basin and irrigation-district levels, those at the village and plot levels remain in progress (Cao & Fan, 2015). Moreover, most farmers in northern China are still unaware of this policy (Figure 3). Only 7% of village leaders in the sample said that they had knowledge of such a policy. In Inner Mongolia and Liaoning Provinces, 17% and 10% of village leaders knew of it, respectively; in other provinces, fewer than 10% did.

Despite the central and local governments' efforts towards water quota management, implementation remains hard in rural areas, for three reasons. First, water use differs across crops, farmers, and regions; it is time-consuming and highly technical to calculate a suitable water quota that can be applied in the field. Second, measurement facilities for irrigation rarely exist in the field. Third, no water rights system has yet been established in China, and the relationship between water quotas and this system is unclear. The interviews with local officials revealed that many are confused on this. In practice, water quotas are more often treated as the initial allocation of water use rights

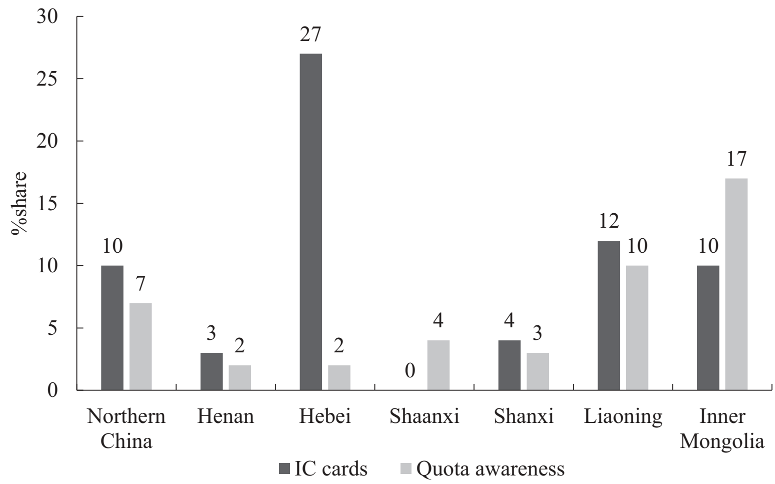

Figure 3. Share of villages with integrated circuit cards on tubewells and awareness of the quota policy.
Source: Authors' survey in 2004 and 2016 (North China Water Resource Survey data-set).

among water users, and trading is typically allowed at the local level (e.g. within the same village or river basin) to increase allocative efficiency. However, this needs to be made clear in legislation.

Water resources fees

Kemper (2007) indicated that a water resources fee can provide incentives to use groundwater more efficiently. This is especially true if this fee is tied to the volume of groundwater used. Since the early 1980s, water resources fees have been introduced in certain provinces in northern China, e.g., Tianjin, Shanxi and Beijing (Shen, 2015); they are also included in the 2002 Water Law. In 2006, the central government issued the Regulations on the Management of Water Abstraction and Permit and Collection of Water Resources Fee. The fee is collected by the water administration departments at the county level based on approved water abstraction permits. Where an abstraction permit is approved by river basin management organizations, the fee is collected by the relevant provincial department for the location of the water intake, based on the actual water abstraction volume and fee standards (Shen, 2015).

However, only users of surface water, or those of groundwater in urban areas, incur a water resources fee. Collecting groundwater resources fees in rural areas remains a major challenge for policy makers. Groundwater fees for irrigation include pumping costs (e.g. tubewells, electricity, diesel) and do not account for the scarcity value of groundwater. The central government has recently encouraged local governments to try a pilot groundwater resources fee in rural areas. It is also planning to transform the fee into a tax to enhance its potential role, selecting Hebei as the pilot province. However, as Yu, Geng, Heck, and Xue (2015) pointed out, the water price does not include the groundwater resources fee in most parts of rural China; it only includes water collection, water infrastructure and water treatment. Despite these efforts, the progress of implementing water resources fees remains slow. According to the field survey, only 2% of villages in northern China collected groundwater resources fees in 2015, for two reasons. First, given the low revenue earned from agricultural production by farmers, it is difficult to implement this policy. Second, facilities that can measure and monitor the groundwater use of individual farmers are lacking. Installing IC cards is a possible method.

Installing integrated circuit cards on tubewells

IC cards are a way to directly regulate the pumping rates of individual farmers. In rural China, the majority of the pumping cost is the cost of the energy to run the pump. In areas where electric pumps are used, the cost of groundwater is largely the cost of electricity. The payment for groundwater is collected by well operators or electricians in the villages. A large share of the payment is then turned over to the county electricity department that supplies electricity to the village. In these areas, IC cards can be used to control groundwater withdrawal by individual farmers. The IC card works like a debit card (Aarnoudse, Qu, Bluemling, & Herzfeld, 2016; Li & Perret, 2015; Wang, Shao, van Steenbergen, & Zhang, 2017b). Prior to irrigation, a farmer deposits money into the IC card. The volume of groundwater the farmer is allowed to pump is then calculated based on the amount the farmer has deposited, the price of electricity, and the flow rate of the pump. The pump stops operating once the allowed volume is reached.

This is not a method stipulated by the central government. But it directly correlates with some national water regulations (e.g. the reform of comprehensive agricultural water price policy in 2012), which suggest improving the measurement of water withdrawal (MWR, 2008; NDRC and MWR, 2003; NDRC, 2016). In fact, the measurement of water withdrawal directly influences the implementation of other policies, such as quota management and water resources fees. IC cards may induce water savings since they provide a strong link between the volume of groundwater pumped and farmers' out-of-pocket expenses. And since the price of groundwater can rise by increasing the price of electricity, IC cards can also be used for pricing policy.

Over the past two decades, some provinces have begun to install IC cards in pilot sites. Shanxi Province has been using IC cards in pilot sites since the late 1990s, and Hebei, Liaoning, Henan, and Inner Mongolia Provinces have been using them since the 2000s. The purpose of the pilot projects is to demonstrate the benefit of IC cards and induce farmers to adopt this technology voluntarily (Zhang & Wang, 2005). However, IC card adoption remains slow in northern China. In 2015, only 7% of villages had IC cards on their tubewells. Even in Hebei Province, which has the most serious groundwater overdraft, fewer than 30% of villages have installed IC cards. The number is 17% in Inner Mongolia Province and 10% in Liaoning Province. In Henna, Shaanxi, and Shanxi Provinces, it is less than 5%.

Part of the reason for the slow progress is the affordability of the equipment. According to the NCWRS, installing an IC card costs about CNY 3000 per well in most of China. As a result, it is not possible for farmers with tubewells to install one without the financial support of the government. Moreover, fiscal reforms in China since the early 1990s, such as the elimination of the agricultural tax, have removed most of the fiscal resources village leaders used to have (Boyle, Huang, & Wang, 2014). Therefore, IC cards are not prevalent on collective wells either. Hence, although IC cards have produced some positive results in conserving groundwater in northern China, an imperfect policy system, hardware unreliability, and the lack of financial support have all limited implementation (Wang et al., 2017b). Furthermore, groundwater usually contains a lot of sediment, which can also damage IC cards.

Investing in agricultural water-saving technologies

In the past three decades, China's government has invested in WST in rural China. Blanke, Rozelle, Lohmar, Wang, and Huang (2007) classified WST into traditional, household-based and community-based. Both traditional (e.g. land levelling and furrow irrigation) and household-based technologies (e.g. surface pipe, drought-resistant crop, no tillage) are mainly invested in and adopted by farmers. However, although the adoption of traditional and household-based WST is encouraged by the government, it has instead invested heavily in community-based WST such as canal lining, ground pipes, sprinklers, and drip irrigation because of their relatively low investment cost and high possibility of adoption. Community-based WST not only need larger investments, they also cover large areas and cannot be adopted by individual farmers. Policies have also influenced the adoption of WST in the field, such as water price policy, financial subsidies for extending WST, and extension services (Cremades, Wang, & Morris, 2015).

Based on the field survey, in the past two decades, the village coverage of community-based WST has increased significantly in northern China (Table 8). For all samples, the percentage of villages adopting canal lining increased from 18% in 1995 to 40% in 2015, and the percentage of villages adopting ground pipes increased from 10% to 41%. Although the adoption rates for both sprinklers and drip irrigation are lower than those of canal lining and ground pipes, they also increased, from less than 5% in 1995 to nearly 15%.

Importantly, the increase in the village adoption rate of community-based WST has been similar in all six provinces. In 2015, the adoption rate for canal lining was the highest in Shaanxi (65%), and that for ground pipes was the highest in Hebei (77%). The adoption rate for sprinklers was the highest in Henan and Inner Mongolia (18% in 2015), while for drip irrigation, the highest adoption rate was in Inner Mongolia. These various adoption rates across provinces indicate different investment priorities for community-based WST.

The annual investment in community-based WST per village has also increased significantly (Table 9). Compared with 1991–1995, investment in canal lining and ground pipes increased by 24 and 12 times in 2011–2015. For sprinklers and drip irrigation, the investment increase was as high as 66 times. The government is the major investor in both canal lining and ground pipes; for sprinklers and drip irrigation, nearly half of the investment comes from the government. Therefore, it is a major promotor of community-based WST, consistent with its policy of increasing irrigation efficiency (the second Red Line goal).

Farmers' response to increasing groundwater challenges

Drilling more tubewells and privatization of tubewells

Faced with the declining quantity and reliability of resources, farmers have also responded to groundwater challenges. The most common response is sinking more tubewells to ensure agricultural productivity. In the past two decades, the average number of tubewells using groundwater irrigation has increased from 27 to 44 per village (Table 10). All sample provinces present a similar upward trend. More importantly, since the 1980s, with the implementation of rural reform, tubewell investors have shifted from village collectives to individuals or groups of farmers (Wang et al., 2009, 2006). That is, tubewell ownership has changed from collective to

Table 8. Share of villages adopting water-saving technologies in northern China (%, as reported by village leaders).

	Canal lining	Ground pipe	Sprinkler irrigation	Drip irrigation
Northern China				
1995	18	10	4	1
2004	29	26	10	2
2015	40	41	14	13
Henan				
1995	21	2	16	0
2004	27	13	18	2
2015	30	27	18	2
Hebei				
1995	11	27	2	2
2004	11	52	4	2
2015	16	77	16	7
Shanxi				
1995	29	26	3	1
2004	37	45	5	1
2015	49	58	8	5
Shaanxi				
1995	21	4	1	0
2004	60	18	6	0
2015	65	35	8	3
Liaoning				
1995	3	1	0	0
2004	15	8	14	4
2015	29	11	17	10
Inner Mongolia				
1995	13	1	1	0
2004	26	24	15	1
2015	42	39	18	44

Source: Authors' survey in 2004 and 2016 (North China Water Resource Survey data-set).

Table 9. Investment in water-saving technologies (as reported by village leaders).

	Annual total investment (yuan/y per village)			Share of government investment (%)		
	Canal lining	Ground pipes	Sprinkler / drip irrigation	Canal lining	Ground pipes	Sprinkler / drip irrigation
1991–1995	1,190	1,380	257	63	12	60
1996–2000	2,114	4,130	2,062	44	27	72
2001–2005	4,571	6,902	1,885	62	78	97
2006–2010	11,115	3,300	2,706	72	89	72
2011–2015	29,635	16,807	17,154	99	92	50

Note: Constant values in 2015
Source: Authors' survey in 2004 and 2016 (North China Water Resource Survey data-set).

private tubewells (including both individual and shareholding tubewells). In 1995, 42% of tubewells were privately owned by farmers (Table 10). Among them, 35% belonged to individual farmers and 7% to shareholding farmers. By 2015, the percentage of private tubewells had increased to 67%, and individual tubewells, 56%. With the privatization of tubewells, the share of collective tubewells decreased from 58% in 1995 to 33% in 2015. Wang et al. (2006) found that the sinking groundwater table is one of the major reasons for the privatization of tubewells in northern China. Therefore, the privatization of tubewells is one of farmers' responses to increasing groundwater challenges (Wang et al., 2009).

Table 10. Number and share of each type of ownership in northern China's villages.

	Number of tubewells per village				Share of each type of ownership(%)		
	Total	Collective tubewells	Shareholding tubewells	Individual tubewells	Collective tubewells	Shareholding tubewells	Individual tubewells
Northern China							
1995	27	16	2	9	58	7	35
2015	44	14	5	25	33	11	56
Henan							
1995	17	14	1	2	85	1	14
2015	24	19	2	3	79	7	14
Hebei							
1995	19	12	5	2	64	27	9
2015	23	14	7	2	63	30	7
Shaanxi							
1995	18	15	0	3	82	0	18
2015	34	7	1	26	21	3	76
Shanxi							
1995	7	6	0	1	88	0	12
2015	9	7	1	1	83	3	14
Liaoning							
1995	77	30	0	47	39	0	61
2015	109	9	12	88	8	11	81
Inner Mongolia							
1995	25	15	4	6	64	16	20
2015	59	25	5	29	42	8	50

Source: Authors' survey in 2004 and 2016 (North China Water Resource Survey data-set).

Although the share of private tubewells has risen across all provinces, the rate of increase varies widely. The fastest growth was observed in Shaanxi, with an increase of 61 percentage points. The share increased by 31 percentage points in Liaoning Province, which now has the greatest share (92%). A possible explanation is that the water table is shallow in these provinces, and thus the cost of sinking a well is low. Therefore, most farmers can afford to sink their own wells. Indeed, the field trips for the current study revealed hundreds of private wells across the villages in Liaoning. Inner Mongolia also rose 22 percentage points in the share of private wells. In all three provinces, the rapid rise in private wells has reduced the share of collective wells to below 50%. By contrast, the growth rates of private tubewells in Henan, Hebei and Shanxi Provinces were all less than 10 percentage points, and collective tubewells remained in the majority in 2015. Most groundwater users in these provinces pump from deep aquifers, so farmers do not have the capital to install tubewells.

Table 11. Relationship between groundwater table depth and high-value crop-sown areas.

	1995		2004		2015	
Quantile of groundwater table depth	Average depth (m)	High-value crop area (%)	Average depth (m)	High-value crop area (%)	Average depth (m)	High-value crop area (%)
Northern China						
0–25%	5.3	14.4	5.6	16.9	9.4	10.3
25–50%	13.9	14.2	16.1	22.8	25.8	15.3
50–75%	27.3	16.0	31.3	19.7	54.0	18.9
75–100%	64.3	17.2	70.9	23.3	113.4	15.5

Source: Authors' survey in 2004 and 2016 (North China Water Resource Survey data-set).

Planting high-value crops

The share of cultivated land allocated to high-value crops increased at the same time as the groundwater table sank. Table 11 divides sample villages into four groups based on the quartile of the groundwater table depth. For each quartile, the average groundwater table continued to sink over the three sample years. The change was considerably larger for the top two quartiles. For the first quartile, the average depth almost doubled from 1995 to 2015, with a drop of almost 50 m. Also, villages in higher quartiles allocated a higher share of their land to high-value crops. For example, in 2015, villages in the bottom quartile had an average groundwater table depth of 9.4 m and allocated 10.3% of land to high-value crops. By contrast, villages in the third quartile had an average depth of 54 m and allocated 18.9% of land to high-value crops. The same correlation is observed for 1995 and 2004. The data also reveal that if the groundwater table were to sink considerably, the share of high-value crops could reverse and begin to decline. This pattern is observed when comparing the third quartile of 2015 sample villages, with an average water table depth of 70.9 m, with the top quartile, with an average depth of 113.4 m. The share of high-value crops dropped from 18.9% to 15.5%. The same is observed when comparing the top quartile of 2004 sample villages, with an average water table depth of 70.9 m, with the top quartile of 2015 sample villages. The share of high-value crops for the 2015 sample is lower (23.3% versus 15.5%).

These findings indicate a possible non-linear relationship between groundwater table depth and cropping patterns, particularly the choice between grain and cash crops. In general, to maximize crop revenue with a lower groundwater table and greater irrigation cost, farmers would like to allocate more land to cash crops. But if the groundwater table continues to sink and even cash crops cannot earn sufficient net revenue to compensate for the high irrigation cost, farmers may choose to plant grain crops to sustain their basic food requirement and find other ways to earn more money. However, since this study did not control for the factors influencing farmers' cropping patterns (e.g. agricultural subsidies, market price of production inputs, and output price), no robust conclusions can be drawn. To reveal the actual relationship between groundwater depth and farmers' cropping patterns, further quantitative analysis (e.g. using econometric models) needs to be conducted.

Other responses to the declining groundwater table

The NCWRS asked village leaders to report their observations of changes in the groundwater table. If a village leader reported a declining groundwater table, follow-up questions were asked about farmers' responses to the problem. Table 12 summarizes these responses.

In addition to digging more private tubewells and planting high-value crops, most village leaders undertook other measures to cope with groundwater unreliability (Table 12). In 1993–1995, 59% of villages were already sinking deeper wells than before. The share of villages using this strategy increased to 69% between 2013 and 2015. Sinking deeper tubewells was the main strategy used by farmers in all provinces. In fact, by 2015, almost all the villages in Henan Province (96%) were sinking deeper wells. At the same time, farmers began using pumps with higher horsepower: 56% villages changed pumps between 2013 and 2015, 12 percentage points more than in the previous two periods. In Hebei Province, this share reached 80%. Although these two measures are likely to temporarily improve the reliability of groundwater irrigation supply, they are short-term solutions. Both measures

Table 12. Responses of farmers to sinking groundwater table (as reported by village leaders).

	Villages (%) with sinking groundwater table that used this measure:					
	Sink deeper tubewell	Change pumps	Adopt water-saving technologies	Adjust crop mix	Reduce irrigation	Use more surface water
Northern China						
1993–1995	59	44	50	19	24	19
2002–2004	66	54	58	27	31	15
2013–2015	69	56	36	16	18	15
Henan						
1993–1995	77	73	68	32	41	41
2002–2004	88	81	73	31	69	27
2013–2015	96	74	30	11	19	19
Hebei						
1993–1995	48	43	52	5	11	2
2002–2004	59	63	57	10	10	4
2013–2015	65	80	50	13	28	9
Shaanxi						
1993–1995	72	56	36	24	36	48
2002–2004	88	67	46	38	33	46
2013–2015	65	55	20	25	20	45
Shanxi						
1993–1995	50	38	42	8	8	17
2002–2004	53	47	56	9	19	6
2013–2015	48	42	42	10	13	13
Liaoning						
1993–1995	64	19	56	25	44	25
2002–2004	62	31	55	31	52	24
2013–2015	71	33	17	25	17	21
Inner Mongolia						
1993–1993	57	33	50	30	23	3
2002–2004	64	41	59	48	27	7
2013–2015	70	44	40	18	12	4

Source: Authors' survey in 2004 and 2016 (North China Water Resource Survey data-set).

may increase the quantity of groundwater pumped out of aquifers, which in turn can exacerbate the already severe water shortage. Another concerning trend revealed by the data is the declining shares of villages that used WST. This share dropped from 50% in 1993–1995 to 36% between 2013 and 2015. This trend was consistently observed across all sample provinces. A possible explanation is that ageing irrigation equipment such as underground pipes was not repaired or replaced, resulting in a lower use rate. The conversion of surface water irrigation may also have alleviated pressure on groundwater resources. Unfortunately, the share of villages that used this measure as a response also declined, from 19% in 1993–1995 to 15% between 2013 and 2015. The drop was most likely because of a lack of available surface water supply. Developing surface irrigation infrastructure is a viable strategy for areas with abundant surface water resources.

Concluding remarks

This study has reviewed groundwater irrigation development over the past two decades in northern China and examined the measures taken by the government and farmers in response to increasing water challenges. The data come from 2004 and 2016 field surveys in six provinces in northern China, covering information for three periods, 1995, 2004, and 2015. We find that in the past 20 years, groundwater irrigation has continued to expand, and nearly 70% of villages or irrigated areas rely on groundwater for irrigation. Importantly, the expansion of groundwater-irrigated areas has accelerated in the past 10 years, and groundwater irrigation is expanding more rapidly in Liaoning and Inner Mongolia. Therefore, policy makers should invest greater efforts in managing groundwater in these two regions, to prevent serious groundwater overdraft problems such as those in Hebei Province, a key region in the Hai River basin.

With the expansion of groundwater irrigation, an issue that needs to be addressed is the increasingly unreliable groundwater supply. The share of villages with reliable groundwater irrigation supply dropped from 68% in 1993–1995 to 53% in 2013–2015. That is, almost half of the villages in northern China do not have reliable groundwater irrigation supply. The purpose of expanding groundwater irrigation is to ensure the productivity of agricultural production and food security. However, the present survey suggests that expanding groundwater irrigation reduces supply reliability. Therefore, if the expansion of groundwater irrigation does not account for the possible consequences of declining supply reliability, its role in improving agricultural production needs to be carefully considered. It is imperative that policy makers strike a balance between expanding groundwater irrigation and improving the supply reliability of existing groundwater irrigation.

The development of groundwater irrigation has also resulted in a sinking groundwater table, groundwater overdraft, and deterioration in groundwater quality. The survey results show that most villages in northern China have experienced a decline in the groundwater table over the past 20 years. Most alarmingly, the share of villages with groundwater overdraft (a decline of 1.5 m/y) has risen sharply, from 8% in 1995–2004 to 34% in 2005–2015. Further, the quality of groundwater has deteriorated. The share of villages that rated their groundwater as good dropped from 60% in 1995 to 39% in 2015. In addition to industrial wastewater pollution, the negative impacts of agricultural activities on groundwater quality are reported in more sample villages in recent years.

The central and local governments have adopted formal and informal policy measures to deal with increasing groundwater challenges, such as well-drilling permits and well-spacing policies, quota management and water resources fees, local pilot project measures (IC cards on tubewells), and investment in community-based WST (e.g. canal lining, ground pipes, sprinklers, drip irrigation). While these policies are implemented in a growing number of villages, their reach remains limited.

The field survey found that the most effective policy measure is the adoption of community-based WST. This finding indicates that the government has put more efforts into improving irrigation efficiency. Owing to the high implementation cost and poor water measurement, both quota management and water resources fees have made little implementation progress. Although IC cards can measure and reduce groundwater withdrawal, their high investment cost has prohibited extension in the field. Finally, the implementation of both well-drilling permits and well-spacing policies is mainly influenced by local officials' decisions.

Farmers have responded to changes in groundwater resources by sinking more and deeper tubewells, changing the crop mix, and adopting WST. However, some of these actions have accelerated the extraction of groundwater. Therefore, significant efforts are needed to improve the effectiveness of policy implementation and steer farmers' behaviour towards more sustainable groundwater use. More importantly, national groundwater legislation is urgently needed, as well as a distinct groundwater management institution. When issuing national legislation, good local policy measures (e.g. well-drilling permits, well-spacing policies) should be included in national implementation guidance. Government policies (e.g. subsidy and tax policies) inducing farmers' positive responses (e.g. changing the crop mix, adopting WST) or prohibiting their negative responses (e.g. sinking more and deeper tubewells) should be promoted and implemented in the field. Finally, considering the high implementation cost of IC cards, how to link existing electric meters in tubewells with groundwater measurement should be addressed by policy makers.

Notes

1. In statistics and econometrics, panel data are multidimensional data involving measurements over time. Panel data contain observations of multiple phenomena obtained over multiple time periods for the same firms or individuals.
2. In the survey, we use the share of irrigated areas to indicate the degree of water scarcity.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work was supported by the National Natural Science Foundation of China [41861124006, 71874007 and 71742002].

References

Aarnoudse, E., Qu, W., Bluemling, B., & Herzfeld, T. (2016). Groundwater quota versus tiered groundwater pricing: Two cases of groundwater management in north-west China. *International Journal of Water Resources Development*, 33(6), 917–934. doi:10.1080/07900627.2016.1240069.

Aeschbach-Hertig, W., & Gleeson, T. (2012). Regional strategies for the accelerating global problem of groundwater depletion. *Nature Geoscience*, *5*(12), 853–861. doi:10.1038/ngeo1617

Blanke, A., Rozelle, S., Lohmar, B., Wang, J., & Huang, J. (2007). Water saving technology and saving water in China. *Agricultural Water Management*, *87*, 139–150. doi:10.1016/j.agwat.2006.06.025

Boyle, C. E., Huang, Q., & Wang, J. (2014). Assessing the impacts of fiscal reforms on investment in village-level irrigation infrastructure. *Water Resources Research*, *50*(8), 6428–6446. doi:10.1002/2013WR015125

Cao, J., Cheng, X., & Li, X. (2009). Groundwater use and its management: Policy and institutional options in rural areas of North China. In A. Mukherji, K. G. Villholth, B. R. Sharma, & J. Wang (Eds.), *Groundwater governance in the Indo-Gangetic and Yellow River basins: Realities and challenges* (pp. 201–220). Boca Raton, FL: CRC Press.

Cao, Y., & Fan, K. (2015). Discuss the role of water quota in water resources management. *Huai River Management*, *11*, 37–38.

Cremades, R., Wang, J., & Morris, J. D. (2015). Policy supports, economic incentives and the adoption of agricultural water-saving technology in China. *Earth System Dynamics*, *6*, 399–410. doi:10.5194/esd-6-399-2015

Foster, S., Chilton, J., Cardy, F., & Schiffler, M. (2000). *Groundwater in rural development: Facing challenges of supply and resources sustainability*. (World Bank Technical Paper, No. 463). Washington, USA: World Bank.

Frija, A., Dhehibi, B., Chebil, A., & Villholth, K. G. (2015). Performance evaluation of groundwater management instruments: The case of irrigation sector in Tunisia. *Groundwater for Sustainable Development*, *1*, 23–32. doi:10.1016/j.gsd.2015.12.001

Grogan, D. S., Zhang, F., Prusevich, A., Lammers, R. B., Wissera, D., Glidden, S., … Frolking, S. (2014). Quantifying the link between crop production and mined groundwater irrigation in China. *Science of the Total Environment*, *511*, 161–175. doi:10.1016/j.scitotenv.2014.11.076

Guo, H., Zhang, Z., Cheng, G., & Li, W. (2015). Groundwater-derived land subsidence in the North China Plain. *Environmental Earth Sciences*, *74*(2), 1415–1427. doi:10.1007/s12665-015-4131-2

Hua, Y., Moiwo, J. P., Yang, Y., Han, S., & Yang, Y. (2010). Agricultural water-saving and sustainable groundwater management in shijiazhuang irrigation district, North China Plain. *Journal of Hydrology*, *393*(3–4), 219–232. doi:10.1016/j.jhydrol.2010.08.017

Huang, Q., Wang, J., Rozelle, S., Polasky, S., & Liu, Y. (2013). The effects of well management and the nature of the aquifer on groundwater resources. *American Journal of Agricultural Economincs*, *95*(1), 94–116. doi:10.1093/ajae/aas076

Jiang, Y. (2009). China's water scarcity. *Journal of Environmental Management*, *90*(11), 3185–3196. doi:10.1016/j.jenvman.2009.04.016

Kemper, K. E. (2007). Instruments and institutions for groundwater management. In M. Giordano & K. G. Villholth (Eds.), *The agricultural groundwater revolution: Opportunities and threats to development* (pp. 153–172). Wallingford: Cabi.

Li, H., & Perret, S. R. (2015). Irrigation management reform in northern China: Case studies in Shanxi province. *Irrigation and Drainage*, *64*, 193–204. doi:10.1002/ird.1901

Li, Y., Zhang, Q., Wang, D., Yang, B., Zhi, X., Fan, S., … Sun, G. (2015). The performance of a predictive risk model for arsenic contamination in groundwater throughout china at the county level. *Fresenius Environmental Bulletin*, *24*(9A), 3057–3062. Retrieved from http://www.prt-parlar.de/

Liu, J., & Zheng, C. (2016). Towards integrated groundwater management in China. In *Integrated Groundwater Management* (pp. 455–475). Cham, Switzerland: Springer.

Madani, K., & Dinar, A. (2013). Exogenous regulatory institutions for sustainable common pool resource management: Application to groundwater. *Water Resources and Economics*, *2–3*, 57–76. doi:10.1016/j.wre.2013.08.001

MLR. (2006). *Technical requirement for function evaluation and zoning of groundwater*. Ministry of Land and Resources. Retrieved from https://wenku.baidu.com/view/89f8dcb269dc5022aaea0001.html

MOHURD. (2010). *Technical code for water wells*. Ministry of Housing and Urban-Rural Development. Beijing: China Planning Press.

Molle, F. (2009). Water scarcity, prices and quotas: A review of evidence on irrigation volumetric pricing. *Irrigation and Drainage Systems*, *23*, 43–58. doi:10.1007/s10795-009-9065-y

MWR. (2005). *The national technical guidance on groundwater function zone*. Ministry of Water Resources. Retrieved from https://wenku.baidu.com/view/e75ef3e8647d27284a735190.html

MWR. (2008). *The time background and the promoting process of the comprehensive reform of agricultural water price*. Ministry of Water Resources. Retrieved from http://www.xiaokaihe.com/Article_Print.asp?ArticleID=669

MWR. (2012). *The technical guideline for groundwater overdraft zone assessment*. Ministry of Water Resources. Retrieved from http://www.doc88.com/p-7774790555821.html

MWR. (2013). The First National Census for Water. Ministry of Water Resources. Retrieved from. http://www.mwr.gov.cn/2013pcgb/index.html

NDRC and MWR. (2003, July 03). *Measures of the management of water supply price for water conservancy engineering*. National People's Congress Standing Committee. Retrieved from http://www.mwr.gov.cn/zw/zcfg/bmgz/201707/t20170714_960242.html

NDRC. (2016). *Notification of pilot scheme for promoting the comprehensive reform of agricultural water price*. National Development and Reform Commission. Beijing: China Planning Press.

NPCSC. (2002, August 29). *Water law of the People's Republic of China*. National People's Congress Standing Committee. Retrieved from http://www.gov.cn/fwxx/content_2265095.htm

NPCSC. (2016). *Report on the implementation of the water law*. National People's Congress Standing Committee. Retrieved from http://www.npc.gov.cn/npc/xinwen/2016-10/12/content_1999020.htm

Qiu, J. (2010). China faces up to groundwater crisis. *Nature*, *466*, 308. doi:10.1038/466308a

Shah, T. (2008). Governing the groundwater economy: Comparative analysis of national institutions and policies in South Asia, China and Mexico. In V. Ballabh (Ed.), *Governance of water: Institutional alternatives and political economy* (pp. 237–266). Delhi: Sage Publications.

Shen, D. (2015). Groundwater management in China. *Water Policy*, *17*, 61–82. doi:10.2166/wp.2014.135

State Council. (2006). *Management regulations for water withdrawal permission and water resources fee collection*. State Council. Retrieved from http://www.gov.cn/zhengce/content/2008-03/28/content_2320.htm

State Council. (2012). *Opinions on the implementation of the strictest water resources management system*. State Council. Retrieved from http://www.gov.cn/zwgk/2012-02/16/content_2067664.htm

Theesfeld, I. (2010). Institutional challenges for national groundwater governance: Policies and issues. *Groundwater*, *48*, 131–142.

Wang, J., Huang, J., Rozelle, S., Huang, Q., & Blanke, A. (2007). Agriculture and groundwater development in Northern China: Trends, institutional responses, and policy options. *Water Policy*, *9*(Suppl. 1), 61–74. doi:10.2166/wp.2007.045

Wang, J., Huang, J., Rozelle, S., Huang, Q., & Zhang, L. (2009). Understanding the water crisis in Northern China: How do farmers and the government respond? *International Journal of Water Resources Development*, *25*(1), 141–158. doi:10.1080/07900620802517566

Wang, J., Li, Y., Huang, J., Yan, T., & Sun, T. (2017a). Growing water scarcity, food security and government responses in China. *Global Food Security*, *14*, 9–17. doi:10.1016/j.gfs.2017.01.003

Wang, J., Xu, Z., Huang, J., & Rozelle, S. (2006). Incentives to managers or participation of farmers in China's irrigation systems: Which matters most for water savings, farmer income, and poverty? *Agricultural Economics*, *34*(3), 315–330. doi:10.1111/j.1574-0864.2006.00128.x

Wang, X., Shao, J., van Steenbergen, F., & Zhang, Q. (2017b). Implementing the prepaid smart meter system for irrigated groundwater production in northern China: Status and problems. *Water*, *9*, 379. doi:10.3390/w9060379

Yu, X., Geng, Y., Heck, P., & Xue, B. (2015). A review of China's water management. *Sustainability*, *7*, 5773–5792. 10. 3390/su7055773 doi:10.3390/su7055773

Zhang, L., & Wang, J. (2005). Application and influence of IC system in the tubewell irrigation. *Journal of Economics of Water Resources*, *23*(2), 42–44.