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Village-level supply reliability of groundwater irrigation in rural China: Effects of climate variables and tubewell density

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Effects of climate variables and tubewell density

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Abstract

Purpose – The purpose of this paper is to examine the status of the supply reliability of groundwater irrigation, and discuss how it is affected by climate change and tubewell density in rural China.
Design/methodology/approach – This study is based on a nine-province village survey and secondary climate data. A Tobit model (or censored regression model) was used to estimate the determinants of supply reliability of groundwater irrigation.
Findings – Results show that the supply reliability of groundwater irrigation was 89 percent on average in the past three years. The non-linear relationship in the econometric results revealed that the 30-year annual temperature significantly influenced the supply reliability of groundwater irrigation. When the temperature rises above the turning point (6.30°C), it shifts from a positive to a negative relationship with the supply reliability of groundwater irrigation. The 30-year annual temperature in eight of the nine provinces (i.e. except for Jilin Province) was higher than the turning point. If the temperature increases by 20°C in the future, other factors being constant, the supply reliability of groundwater irrigation will decline by 20 percent. However, if precipitation increases by 10 percent, the supply reliability of groundwater irrigation could improve by 3 percent, while reducing precipitation by 10 percent will lower the supply reliability of groundwater irrigation by 3 percent. Increasing the density of tubewells considerably improves the supply reliability of groundwater irrigation. However, although increasing the density of tubewells may yield enough groundwater for irrigation, this one-sided approach raises sustainability concerns.
Research limitations/implications – Although increasing the density of tubewells may ensure that enough groundwater is available for irrigation, such a conclusion is one sided, and sustainability concerns should be raised in assessing this method of creating supply reliability.

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The manuscript expands on the existing conference (9th ASAE International Conference 2017) paper "Supply Reliability of Groundwater Irrigation, Climate Change, and Tube Well Density in Rural China."

Originality/value – This paper improves the understanding of the impact of climate variables on agriculture irrigation and water supply reliability in the micro scale, and provides a scientific basis for relevant policy making.

Keywords Temperature, Precipitation, Groundwater irrigation, Supply reliability, Tubewell density

Paper type Research paper

1. Introduction

Agricultural production in China relies heavily on groundwater resources, leading to serious environmental issues. In Northern China, 68 percent of irrigation supply comes from groundwater (Wang *et al.*, 2007). Consequently, the groundwater table has declined by more than 1 m (and at times, even more than 2 m) per year in Northern China (Wang *et al.*, 2009). Although having relative rich surface water resources, some places in Southern China also experience groundwater overexploitation (Guo *et al.*, 2005; Yuan *et al.*, 2001; Zhao *et al.*, 2008; Zhang *et al.*, 2016). For instance, the groundwater table in the Suxichang Region of Jiangsu decreased at an average annual rate of 1–3 m due to excessive long-term mining (Yuan *et al.*, 2001). Importantly, the decline of groundwater has resulted in some other environmental issues, such as depression cones, land subsidence, groundwater pollution and seawater intrusion (Shen, 2016; Wen, 2015; Tian *et al.*, 2011, 2012).

Furthermore, the sustainable development of groundwater has been challenged by climate change and expansion of tubewells. Climate change is projected to reduce renewable groundwater resources significantly in most dry subtropical regions (Field *et al.*, 2014). Aguilera and Murillo (2009) found that groundwater recharge decreased strongly during the twentieth century. This is not only due to decreasing precipitation but also possibly because of an increase in evapotranspiration. In addition, the expansion of tubewells is driven by government support and farmers' profit maximization behavior, which results in the overexploitation of groundwater in rural China. Before 1980s, tubewell investments in China were mainly supported by government and village management committees. However, with the implementation of rural reforms since the 1970s and the decline in the collective economy, individual farmers have become major investors in tubewells (Wang *et al.*, 2005). Farmers invest in tubewells to increase agricultural productivity and earn more money. Unfortunately, due to poor management, this trend has accelerated the decline in the groundwater table (Wang *et al.*, 2009). With falling groundwater levels, tubewells had to be abandoned and replaced with new, deeper systems (Wang *et al.*, 2007; Sun *et al.*, 2009).

An important question in this context is: how reliable is groundwater supply for irrigation in rural China? This issue involves considering whether farmers have a sufficient and timely supply of groundwater available for irrigation purposes. It also involves assessing the current status and future trends of the supply reliability of groundwater irrigation in China. Furthermore, whether climate change affects the supply reliability of groundwater irrigation and how significant this influence might be are important considerations for explaining this phenomenon. It is important to also explain the relationship between supply reliability of groundwater irrigation and tubewell development. Specifically, whether increasing tubewell density will positively affect the reliability of groundwater supply needs to be considered. With an understanding of these issues, policy makers can assist farmers to increase agricultural productivity and realize sustainable use of groundwater.

However, most of the available literature primarily focuses on the effects of climate change on the magnitude, timing or mechanisms of groundwater recharge, and almost all these studies are global-scale overviews based on secondary data (Kundzewicz and DÖll, 2009; Green *et al.*, 2011; Treidel *et al.*, 2012; Chen *et al.*, 2004), rather than micro-level perspectives that focus, for instance, on the level of villages, conducted using field data. In addition, these studies are not based directly on empirical analysis, but on the application of hydrological models (Kløve *et al.*, 2014; Döll, 2009; Kundzewicz and DÖll, 2009; Treidel *et al.*, 2012; Jackson *et al.*, 2011). A few studies have shown that whether farmers have a reliable irrigation supply depends on some social and economic factors such as available water facilities, type of water facilities and characteristics of the community and household (Yang *et al.*, 2012; Cheng and Wang, 2008). However, these studies have not considered the effects of climatic factors.

The current study is an attempt to address this gap. The paper aims to examine the status of supply reliability of groundwater irrigation and how this is affected by climate variables and tubewell density at the village level in rural China. This paper has three specific objectives: the first is to understand the climate change trends over the past 30 years, the present context of tubewell use and the system density in rural China. The second is to examine the supply reliability status of groundwater irrigation over the past three years and explore how farmers respond to the factors behind the unreliable supply of groundwater irrigation. The third is to quantify the influence of both climate variable and tubewell density on the supply reliability of groundwater irrigation.

The paper is organized as follows: Section 2 introduces data collection and model specification. Section 3 contains descriptive statistics, for instance, climate change (both temperature and precipitation), irrigation sources, tubewell density and the supply reliability of groundwater irrigation in the sample area and presents econometric analyses of the factors that influence the supply reliability of groundwater irrigation, including climate variables, tubewell density variables and other socio-economic variables. The final section concludes the paper and provides some policy implications.

2. Data collection and model specification

2.1 Sampling approach and field survey data

The data used in this study were collected from a large-scale field survey conducted in late 2012 and early 2013 across nine provinces in China: Hebei, Henan, Shandong, Jiangsu, Anhui and Jilin in Northern China and Jiangxi, Guangdong and Yunnan in Southern China. These provinces were selected based on their differences in water resources and climate features, as well as their diverse patterns of economic development. Specifically, Hebei, Jilin, Henan, Jiangsu and Anhui have less precipitation, while Guangdong, Jiangxi and Yunnan are characterized by abundant precipitation and water resources. Our sample includes provinces both in Northern and Southern China, and they are all important agricultural production regions. To an extent, these features mean our sample could be viewed as a nationally representative sample.

The following strategies were used for the selection of the sample. Three counties in each province were randomly selected, with the exception of Jiangxi and Guangdong, where ten and six counties, respectively, were selected. Within each selected county, a stratified random sampling technique was used to select three townships from each county and three villages from each township. Villages were stratified into three groups by the conditions of their rural water infrastructure: above average, average or below average. Finally, 330 villages in 37 counties were selected from the 9 provinces. Since the analysis was limited to groundwater reliability, villages that do not use groundwater for irrigation were excluded. The final sample consisted of 142 villages in 26 counties in 9 provinces. The sample distribution of the survey is summarized in Table AI.

The village-level questionnaires were designed to collect data. While this survey covered a wide range of issues, only data relevant to this study were analyzed. The survey conducted in the villages collected data for only three years: 2010, 2011 and 2012[1]. The first important point was groundwater reliability, meaning whether farmers who wanted to irrigate their crops using groundwater could get enough water and in a timely fashion. If the response was "yes," we defined groundwater supply for irrigation to be reliable; otherwise, it was seen as being unreliable. Specifically, the investigators asked village leaders what percentage of irrigated crop-sown areas could not get sufficient and timely supply of groundwater to satisfy the requirement of crops in the previous three years (2010–2012)[2]. Information on the reasons that led to the unreliable supply of groundwater was also collected[3].

In addition, the survey collected the following information: socio-economic characteristics, such as total cultivated land and number of people in the village; physical characteristics, such as topography (plain or mountain) features and whether the village had a continuous residential population; and irrigation conditions, such as water resources for irrigation (groundwater, surface water or both), and number and depth of shallow and deep tubewells. Shallow and deep tubewells were identified according to their definitions in the local region. Since each region's local hydrological and other physical conditions are different, the definitions of shallow and deep tubewells also differ. Based on information on the number of tubewells and cultivated land areas, this study generated an indicator of tubewell density, number of tubewells per cultivated land area (number/ha).

2.2 Secondary climate data

Climate data were drawn from the National Meteorological Information Center in China. It consisted of monthly maximum, minimum and average temperatures and precipitations from 1960 to 2012 from 756 ground-based meteorological stations located throughout China. The major variables analyzed were monthly average temperature and precipitation, and this information was used to generate 30-year annual temperature and 30-year annual average of precipitation that will be used in our regression analysis. Both temperature and precipitation were assumed to be homogenous within counties.

However, in the 26 sampled counties, only 13 contained meteorological stations. In order to obtain county-level temperature and precipitation data for the other counties, this study used the spatial interpolation method proposed by Thornton *et al.* (1997). This method requires information on digital elevation data and observations of maximum temperature, minimum temperature and precipitation from ground-based meteorological stations. Based on this information, a cross-validation analysis was performed and the predictions of temperature and precipitation levels were validated. The same type of interpolation data were used by Zhang *et al.* (2013) and Hou *et al.* (2015). Descriptive statistics for the data used in this study are summarized in Table AII.

2.3 Specification of econometric model

Although the term "reliability of water supply" has appeared in published studies, it is commonly regarded as being inversely related to the probability of a system shortfall (such as effects of climate change), where demand is greater than the available supply (Clark *et al.*, 2015; Griffin and Mjelde, 2000; Park and Kim, 2014). Typically, it is defined as the volume of water supplied as a percentage of the total demand in a given period (Clark *et al.*, 2015). Most studies on water supply reliability analyze the volume reliability of water supply, which is essentially the rate of water availability. In terms of the reliability of the groundwater irrigation, there are even fewer studies available, especially ones that use data from large-scale village surveys, and there are even fewer that associate this phenomenon with climate change.

Agricultural production depends not only on whether there is sufficient water availability but also, more importantly, on whether farmers can receive a sufficient amount of water when irrigation is needed, namely, sufficient and timely supply of irrigation, or reliability of irrigation supply. A few studies have shown that whether farmers have a reliable irrigation supply depends on some social and economic factors such as available water facilities, type of water facilities and characteristics of the community and household

(Yang *et al.*, 2012; Cheng and Wang, 2008). However, these studies have not considered the effects of climatic factors. In addition, although the influence of irrigation facility type has been examined, the influence of tubewell density has not been considered.

In order to better identify and quantify the impacts of different factors on the reliability of the groundwater supply, the following econometric model was developed:

$$W_{ij} = \alpha_{ij} + \beta_1 C_{ij} + \beta_2 I_{ij} + \beta_3 V_{1ij} + \beta_4 P_{ij} + \varepsilon_{ij} \quad (1)$$

In the model, i and j indicate the ith village in the jth country. Here, W_{ij} indicates the supply reliability of groundwater irrigation, measured by the share of irrigated crop-sown areas having access to a reliable groundwater supply.

The right-hand side of the model includes the following independent variables: C_{ij} is a set of four climate variables: 30-year annual temperature, 30-year annual temperature squared, 30-year annual precipitation and 30-year annual precipitation squared. Considering the possible relationship between temperature and precipitation (their correlation is 0.76), we also included one interactive variable (30-year annual temperature ×30-year annual precipitation) in the model; I_{ij} is a set of two variables that measure the density of shallow and deep tubewells[4]; V_{1-4ij} is a set of four variables that measure village characteristics: whether irrigating by surface water (1 = yes; 0 = no), landform (1 = plain; 0 = mountain), whether there is a continuous residential area (1 = yes; 0 = no), and cultivated land area per person (ha); and P_{ij} is a set of province dummy variables; the purpose of this set of variables is to control for the impact of regional characteristics that do not change over time but might affect the supply reliability of groundwater irrigation. With nine provinces in the sample, the model included eight dummy variables, leaving one of the provinces, Henan, as the default category. The model, in which α_{ij} is a constant, β_1–β_4 are the parameters to be estimated, and ε_{ij} is the random error term, is assumed to be subject to an independent, identical distribution.

According to the analysis of irrigation sources, some of our sample areas use only groundwater and some use both groundwater and surface water for irrigation. To examine whether the impact of climate variables and other factors on supply reliability of groundwater irrigation differs by irrigation source, this study runs two kinds of models. The first is based on the full sample (Column 1 in Table IV), while the second model is limited to the sample area that depends only on groundwater for irrigation supplies (Column 2 in Table IV).

Since our dependent variables were always positive and continuous between 0 and 1, a Tobit model (or censored regression model) was used to estimate the determinants of water reliability. A Tobit model avoids the downward biases that are often generated by ordinary least squares techniques (Wooldridge, 2010). The general formulation of a Tobit model is usually given in the following equations (or index functions):

$$Y_{ij}^* = \partial_i' X_{ij} + \varepsilon_{ij}$$

$$Y_{ij} = 0 \quad \text{if} \quad Y_{ij}^* < 0 \text{ or } Y_{ij}^* = 0$$

$$Y_{ij} = Y_{ij}^* \quad \text{if} \quad Y_{ij}^* > 0 \quad (2)$$

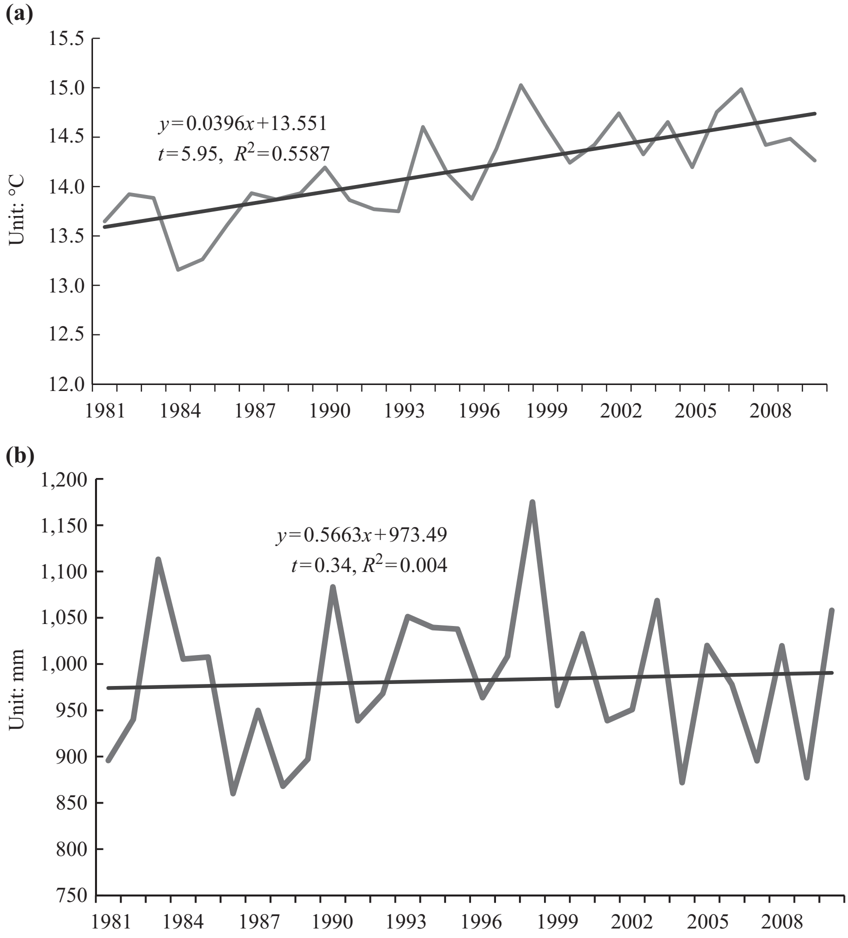
Y_{ij}^* is a latent variable, and its expected value is $\partial_{ij}' X_{ij}$. Y_{ij} is the censored variable that is observed. The set of variables X_{ij} includes all the parameters, and ∂_i reflects the marginal impacts of changes in W_{ij} and Y_{ij} in the models used in this study.

3. Descriptive statistics and estimation results of econometric model

3.1 Climate change over 30 years

Our data analysis shows an increasing trend in average temperature over the past 30 years (1981–2010), which is statistically significant (Figure 1(a)). In the 1980s, the annual temperature for the sample sites was 13.7°C. This number increased to 14.2°C in the 1990s and to 14.5°C in the 2000s; thus, the annual temperature increased by 0.8°C over the 30-year period. In addition, there exists large inter-annual temperature variability. Such changes reflect national and global temperature changes, which have been reported by many other scholars (Ding *et al.*, 2006; Intergovernmental Panel on Climate Change, 2007; The Second National Assessment Report Writing Board, 2011).

Unlike for temperature, there was no obvious variability in the rates of annual precipitation (Figure 1(b)). In this period, the annual precipitation rate has remained



Notes: (a) Variability of annual temperature; (b) variability of annual precipitation
Source: National Meteorological Information Center in China

Figure 1. Variability of annual temperature and precipitation in the last 30 years (1981–2010)

around 970 mm, and it displays a slight upward trend. However, the fluctuation in this rate is much more remarkable, which implies that the inter-annual variability of precipitation may continue to be reflected for a long time.

3.2 Irrigation sources and tubewells

3.2.1 Irrigation sources. Results show that most villages depend on groundwater irrigation. On average, 70 percent of villages were solely dependent on groundwater for irrigation (Figure 2(a)). This number remained relatively constant over the three-year period, ranging from 70 percent in 2010 to 69 percent in 2012. For the other 30 percent of villages, their irrigation system uses a combination of groundwater and surface water. Since villages that

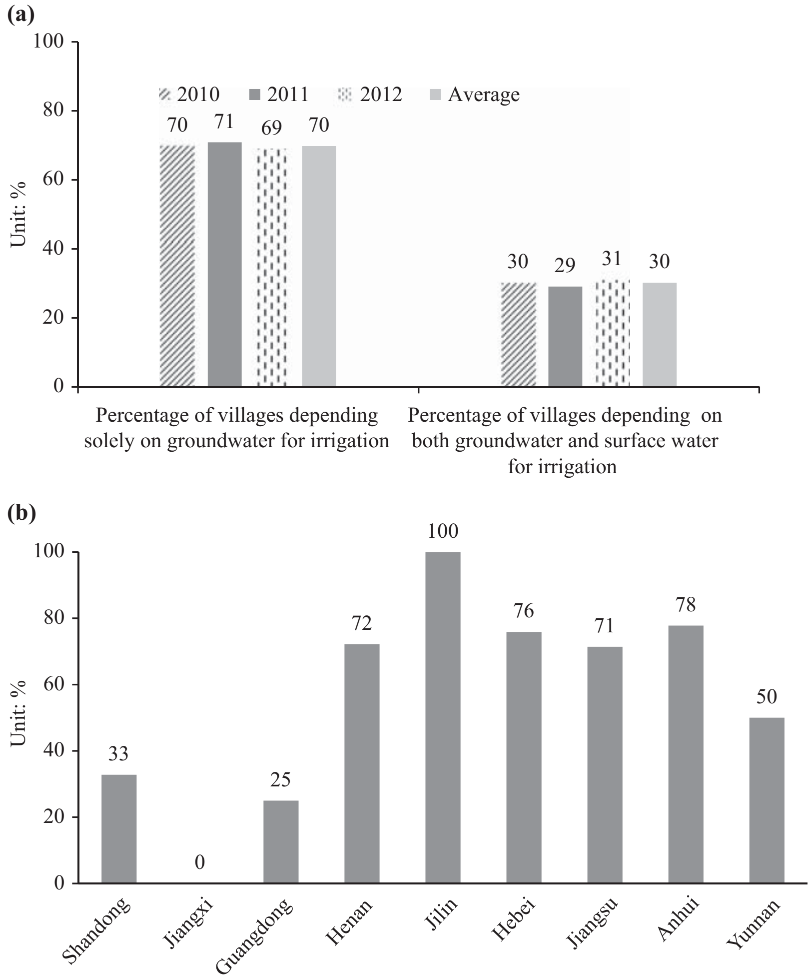


Figure 2.
Irrigation sources over the past three years (2010–2012)

Notes: (a) By year for all provinces; (b) by province for three years' average: depending solely on groundwater irrigation
Source: Authors' survey

do not use groundwater for irrigation were excluded from the sample, no villages in the study area used only surface water for irrigation.

Further analysis indicates that irrigation sources differ by province. In Jilin Province, all the villages were solely dependent on groundwater for irrigation. In Jiangxi Province, however, no one village depended solely on groundwater for irrigation (Figure 2(b)). Therefore, all villages in Jiangxi Province depended on both groundwater and surface water for their irrigation needs. In other provinces, the percentage of villages that only depended on groundwater for irrigation in three provinces (Guangdong, Shandong and Yunnan) was lower than the average number (70 percent as shown in Figure 2(a)). However, in provinces such as Anhui, Hebei, Henan and Jiangsu, more than 70 percent of villages depended solely on groundwater for irrigation.

3.2.2 Number of tubewells and tubewell density. From Table I, the average number of tubewells in each village shows an increasing trend, rising from 50 in 2010 to 56 in 2012. There were more shallow tube wells (57 percent) than deep tube wells (43 percent). The average depth was 30 m for shallow tubewells and 63.4 m for deep tubewells. The percentage of deep tubewells slightly increased over time (from 41 percent in 2010 to 45 percent in 2012). Over the three-year study period, an increasing number of deep tubewells were needed as replacements for shallow tubewells because of the overexploitation of groundwater. Shallow tubewells might have also needed to be abandoned because of the falling water table. In addition, one can draw a distinction between provinces from the viewpoint of number of tubewells or percentage of shallow and deep tubewells. For example, Jiangxi and Guandong Provinces in South China, with more than 80 tubewells in each village, have many more tubewells than other provinces. Jiangxi Province, endowed with relatively rich water resources, did not need deep tubewells.

The density of shallow tubewells was, on average, greater than that of deep ones. Specifically, the density of shallow tubewells was 96 per 1,000 ha, while that of deep tubewells was 71 per 1,000 ha (Table I). The density of both shallow and deep tubewells reflects an increasing trend from 2010 to 2012. In five (Henan, Hebei, Anhui, Jiangsu and Yunnan) of the nine provinces, the density was greater for shallow tubewells than deep tubewells. In Henan Province, for example, the density was 164 per 1,000 ha for shallow

	Number of tubewells in each village	Percentage of shallow and deep tubewells		Tubewell density (number/thousand hectares)	
		Shallow	Deep	Shallow	Deep
Total samples					
Average	53	57	43	96	71
2010	50	59	41	93	64
2011	52	58	42	97	71
2012	56	55	45	98	77
By province					
Hebei	37	75	25	110	47
Henan	23	71	29	164	57
Shandong	26	29	71	74	159
Jilin	22	53	47	61	66
Anhui	25	57	43	87	61
Jiangsu	43	73	27	108	42
Jiangxi	114	100	0	168	–
Guangdong	84	38	62	31	87
Yunnan	18	66	34	24	20

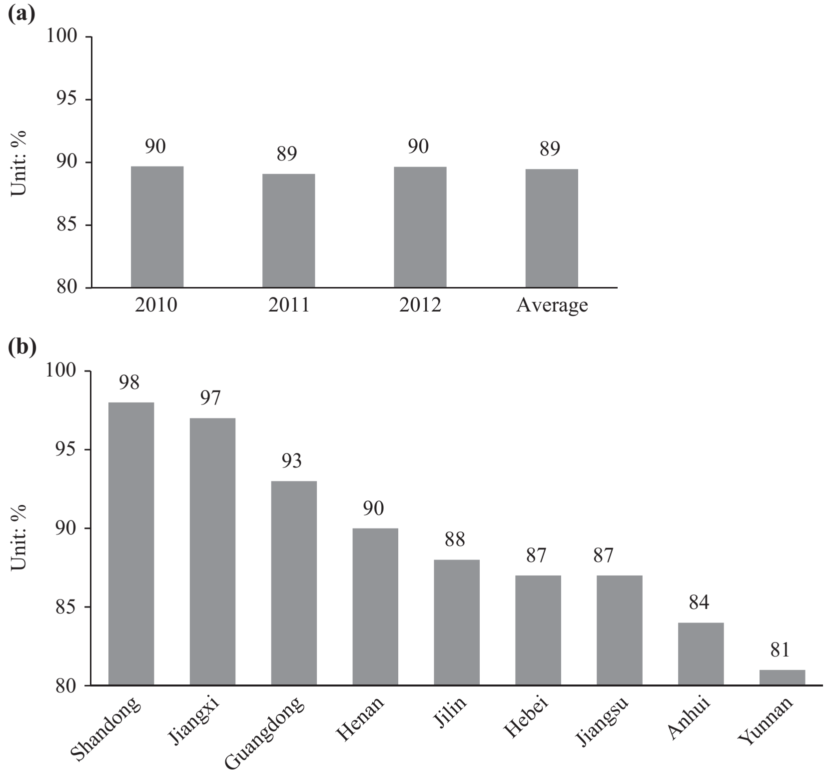
Source: Authors' survey

Table I. Number and density of tubewells in nine Chinese provinces tubewells but only 57 per 1,000 ha for deep tubewells. In the other three provinces (Shandong, Jilin and Guangdong), the density was lower for shallow tubewells than deep tubewells. In Shandong, specifically, the density was 74 per 1,000 ha for shallow tubewells and 159 per 1,000 ha for deep tubewells. Jiangxi Province had only shallow tubewells, with a density of 168 per 1,000 ha, the highest among the nine provinces.

3.3 Supply reliability of groundwater irrigation

As Figure 3(a) shows, the average supply reliability was 89 percent between 2010 and 2012. Second, concerning inter-provincial differences in groundwater supply reliability for irrigation, Shandong and Jiangxi showed high reliability, at 98 and 97 percent, respectively (Figure 3(b)). In Guangdong and Henan, reliability was 93 and 90 percent, respectively. In Jilin, Hebei, Jiangsu, Anhui and Yunnan, the reliability ranged from 88 to 81 percent.

Our study also incorporated an analysis of the reasons for insecure or unreliable groundwater supply. Our field survey found three main causes of this phenomenon. The most important was the very low water table in the villages. Second, tubewells were not maintained efficiently. Third, the villages did not have enough tubewells. Table II clearly shows that, on average, the first problem affected 86.7 percent of the villages, the second 10.6 percent and the third 2.7 percent.



Notes: (a) By year for all provinces; (b) by province for three years' average
Source: Authors' survey

Figure 3.
Percentage of irrigated crop-sown areas having a reliable groundwater irrigation supply over the past three years (2010–012) (percent)

However, the reasons for this unreliable supply were remarkably different between provinces. As shown in Table III, the reason for Shandong, Guangdong, Jilin and Yunnan was a too low water level. Lack of tubewell maintenance was an additional reason, along with a low water table, for Jiangxi, Jiangsu and Anhui. More specifically, in Jiangxi, each factor accounted for 50 percent of the problem. In Jiangsu and Anhui, the water table was too low in 80 percent of the villages. Finally, Henan and Hebei faced a third obstacle—shortage of tubewells in their villages—in addition to the first two mentioned above. However, this accounted for only a tiny fraction (6.7 and 9.1 percent, respectively) of the unreliability problem, and the first factor (too low water table) was still the major cause of the unreliable water supply.

3.4 Estimation results of econometric model

3.4.1 Influence of 30-year annual temperature and precipitation on supply reliability. Both models performed well. The pseudo R^2 values were 0.42 and 0.55, which were reasonably high for multivariate analyses. Furthermore, among two models, the signs of most climate variables, as well as tubewell density and other control variables, were strongly consistent with our expectation, and also statistically significant.

First, estimation results showed that the 30-year annual temperature significantly influenced the supply reliability of groundwater irrigation, and demonstrated a non-linear relationship. Importantly, increasing 30-year annual temperature will reduce the supply reliability of groundwater irrigation in most regions in China. The coefficient of the linear term of 30-year annual temperature was positive and statistically significant in two models (Table IV). This implied that in the future, the supply reliability of groundwater irrigation will increase along with rising temperature. However, this relationship is non-linear, since the squared term of 30-year annual temperature was negative and statistically significant. This indicated that with a further increase in temperature or when the temperature is higher than the turning point, rising temperature will result in a decline in the supply reliability of

Table II. Village leaders' response on the major reasons that result in an unreliable groundwater irrigation supply

	Percentage of villages			
	2010	2011	2012	Average
Water table is too low	87.7	86.3	86.3	86.7
The tubewell has not been maintained in time	9.6	11.3	11.0	10.6
Not enough tubewells	2.7	2.5	2.7	2.7

Source: Authors' survey

Table III. Village leaders' response on the major reasons that result in an unreliable groundwater irrigation supply by province

	Percentage of villages		
	Water table is too low	The tubewell has not been maintained in time	Not enough tubewells
Shandong	100.0	0.0	0.0
Jiangxi	50.0	50.0	0.0
Guangdong	100.0	0.0	0.0
Henan	86.7	6.7	6.7
Jilin	100.0	0.0	0.0
Hebei	72.7	18.2	9.1
Jiangsu	85.7	14.3	0.0
Anhui	82.2	17.8	0.0
Yunnan	100.0	0.0	0.0

Source: Authors' survey

	Share of irrigated crop-sown area having reliable supply of groundwater irrigation	
	All samples[a]	Part samples[b]
Climate variables		
30-year annual temperature (°C)	0.268*** (4.99)	0.380*** (3.82)
30-year annual temperature squared	−0.010** (2.38)	−0.015** (2.38)
30-year annual precipitation (mm)	0.015 (1.34)	0.010 (0.77)
30-year annual precipitation squared	0.000185** (2.34)	0.000316* (1.89)
Interactive variable		
30-year annual temperature × 30-year annual precipitation	−0.002* (1.65)	−0.003 (1.62)
Tubewell density		
Shallow tubewell density (number/ha)	0.281** (2.20)	0.283** (1.98)
Deep tubewell density (number/ha)	0.630*** (3.44)	0.629*** (3.24)
Village characteristics		
Whether irrigating by surface water (1 = yes; 0 = no)	0.055* (1.77)	
Landform (1 = plain; 0 = mountain)	0.069 (1.08)	0.105 (1.30)
Whether having continuous residential areas (1 = yes; 0 = no)	0.048 (1.48)	0.045 (1.20)
Per capita cultivated land area (ha)	−0.247 (1.07)	−0.445* (1.85)
Province dummies[c]		
Hebei	−0.032 (0.45)	−0.036 (0.44)
Yunnan	−0.285** (2.52)	−0.062 (0.35)
Shandong	0.053 (0.92)	0.121 (1.44)
Jilin	−0.029 (0.21)	0.005 (0.03)
Anhui	−0.092 (1.47)	−0.010 (0.16)
Jiangsu	−0.056 (0.70)	−0.056 (0.64)
Jiangxi	−0.139 (0.56)	−0.652 (0.87)
Guangdong	0.918** (2.51)	0.557 (0.58)
Constant	−0.508 (1.21)	−0.791* (1.67)
Observations	414	289
Fit statistics of Tobit		
LR χ^2	133.65	117.15
Log likelihood	−90.8823	−48.2071
Prob. > χ^2	0.0000	0.0000
Pseudo R^2	0.4237	0.5485

Notes: Absolute *t*-statistics in parentheses. [a]Depending solely on groundwater or both groundwater and surface water; [b]depending solely on groundwater; [c]the comparing base for province dummy is Henan Province. We have tried the regression with year dummies, and the coefficients of year dummies are not statistically significant and the estimation results for other variables have not been significantly changed. Therefore, in order to save paper space, we have not included year dummies into the regressions. $*p < 0.10$; $**p < 0.05$; $***p < 0.01$

Table IV. Regression results of the determinants of supply reliability of groundwater irrigation

groundwater irrigation. Based on the estimation, the turning point of 30-year annual temperature is 6.3°C, which can be calculated based on the marginal results of the determinants of supply reliability of groundwater irrigation (Table V). If the region's 30-year annual temperature is higher than 6.3°C, an increasing temperature is harmful for the supply reliability of groundwater irrigation. In all the sample provinces, the 30-year annual temperature in eight provinces was higher than the turning point, except for Jilin, where it was lower. Therefore, in the future, increasing temperatures in the future will lower the supply reliability of groundwater irrigation in most Chinese regions. It is possible that rising temperatures will increase evapotranspiration, impairing groundwater recharge. This, in turn, will negatively affect the supply reliability of groundwater irrigation.

	Share of irrigated crop-sown area having reliable supply of groundwater irrigation	
	All samples[a]	Part samples[b]
Climate variables		
30-year annual temperature (°C)	0.134***	0.206***
30-year annual temperature squared	−0.005**	−0.008**
30-year annual precipitation (mm)	0.001	0.005
30-year annual precipitation squared	0.0000006**	0.000001*
Interactive variable		
30-year annual temperature × 30-year annual precipitation	−0.00009*	−0.00013
Tubewell density		
Shallow tubewell density (number/ha)	0.140**	0.153**
Deep tubewell density (number/ha)	0.315***	0.341***
Village characteristics		
Whether irrigating by surface water (1 = yes; 0 = no)	0.027*	
Landform (1 = plain; 0 = mountain)	0.035	0.057
Whether having continuous residential areas (1 = yes; 0 = no)	0.024	0.024
Per capita cultivated land area (ha)	−0.124	−0.241*
Province dummies[c]		
Hebei	0.126*	0.014
Henan	0.142**	−0.034
Shandong	0.169***	0.099
Jilin	0.128	0.034
Anhui	0.096**	0.028
Jiangsu	0.115**	0.003
Jiangxi	0.073	0.320
Guangdong	0.601***	0.335
Observations	414	289
Fit statistics of Tobit		
LR χ^2	133.65	117.15
Log likelihood	−90.8823	−48.2071
Prob. > χ^2	0.0000	0.0000
Pseudo R^2	0.4237	0.5485

Notes: [a]Depending solely on groundwater or both groundwater and surface water; [b]depending solely on groundwater; [c]the comparing base for province dummy is Henan Province. *$p < 0.10$; **$p < 0.05$; ***$p < 0.01$

Table V. Marginal effects of major determinants of supply reliability of groundwater irrigation

Second, as shown in the estimation results, increasing precipitation significantly benefited all regions in China in regard to the supply reliability of groundwater irrigation. The coefficients of both linear and non-linear terms of 30-year annual precipitation were positive, and the non-linear term was statistically significant (Table IV). The results implied that increasing 30-year annual precipitation rates will improve the supply reliability of groundwater irrigation in the future; in contrast, decreasing 30-year annual precipitation rates will reduce the supply reliability of groundwater irrigation. This is consistent with prior expectation as increasing precipitation will possibly augment groundwater recharge and, in turn, improve the supply reliability of groundwater irrigation.

Considering the correlation between temperature and precipitation, if both temperature and precipitation increase simultaneously, the supply reliability of groundwater irrigation will significantly reduce based on the full-sample estimation. The coefficient of the interactive variable for 30-year annual temperature and 30-year annual average of precipitation was negative in two models. It was statistically significant in the full-sample model (Table IV), but not in another model. For the full sample, this indicated that if the temperature is also higher, the supply reliability of groundwater irrigation will decline even if higher precipitation occurs.

Considering the interactive and non-interactive variables together, one can see the separate impacts of 30-year annual temperature or precipitation on supply reliability of groundwater irrigation, keeping other factors constant. As shown in Table VI, increasing the temperature by 0.5°C, other factors being constant, reduces the supply reliability of groundwater irrigation by 3 percent, from 81 to 78 percent. If the temperature continues to increase, the supply reliability will further reduce. If the temperature increases by 2°C in the future, supply reliability will reduce by 20 percent, from 81 to 61 percent. The effect of precipitation differs from that of temperature as increased precipitation improves supply reliability. For example, as to precipitation, supply reliability increases by 3 percent (from 81 to 84 percent) with a 10 percent increase, increases by 6 percent (from 81 to 87 percent) with a 25 percent increase and increases by 10 percent (from 81 to 91 percent) with a 50 percent increase. Likewise, supply reliability will decline by 3 percent (from 81 to 78 percent), 8 percent (from 81 to 73 percent) and 10 percent (from 81 to 71 percent), if precipitation reduces by 10 percent, 25 and 50 percent, respectively. In summary, temperature is positively and precipitation negatively related to supply reliability on average.

3.4.2 Influence of tubewell density and other control variables on supply reliability. Estimation results also indicate that the higher the tubewell density of a village, the higher (and significantly so) the supply reliability of groundwater irrigation. The coefficients of both shallow and deep tubewell densities were positive and statistically significant in two models (Table IV). Therefore, increasing tubewell density is an important measure to enhance the supply reliability of groundwater irrigation. Specifically, as shown in Table V, if the density of shallow tubewells is increased by one unit (i.e. the number of shallow tubewells is increased by one per ha), other factors being constant, the supply reliability of groundwater irrigation will increase by 14 percent for all sample provinces and by 15 percent for those provinces that rely solely on groundwater. Adding one deep tubewell per ha, all other control factors being constant, increases the supply reliability of groundwater irrigation by 32 percent for all sample areas and by 34 percent for those that solely rely on groundwater (Table V). However, increasing the number of tubewells will accelerate the decline in the groundwater table if no suitable policy measures are

Table VI. Change in groundwater reliability due to climate change in the future

	The percentage of irrigated crop-sown areas having a reliable groundwater supply
Baseline	81
Temperature change	
0.5°C (+)	78
1.0°C (+)	73
1.5°C (+)	67
2°C (+)	61
Precipitation change	
10% (+)	84
25% (+)	87
50% (+)	91
10% (–)	78
25% (–)	73
50% (–)	71

Source: Calculated from regression results of all samples implemented to change farmers' behavior and manage water demand effectively. In the long term, the decline in the groundwater table can increase the investment costs of tubewells, reduce the availability of groundwater supply and affect the supply reliability of groundwater irrigation. Therefore, a suitable scale of tubewell density is an important topic that requires further attention and research.

The results demonstrate that some of the physical and socio-economic conditions of the villages were closely related to water reliability. For instance, the coefficients for the presence of irrigation systems that use surface water were positive and statistically significant (Table IV). In this regard, the supply reliability of groundwater irrigation will be 2.7 percent higher for villages with surface water irrigation than those without. In addition, the supply reliability of groundwater irrigation also differed by province when the full-sample model is run. For instance, the supply reliability of groundwater irrigation in Yunnan Province is statistically lower than Henan Province, the supply reliability of groundwater irrigation in Shandong Province is statistically higher than Henan Province, but in other six provinces (Hebei, Jilin, Anhui, Jiangsu, Shandong and Jiangxi), the supply reliability of groundwater irrigation was not significantly different compared with that in Henan.

4. Results and discussion

Through a large-scale field survey conducted in nine provinces in China, this study examined the trends of both temperature and precipitation changes over the last 30 years, and the supply reliability of groundwater irrigation between 2010 and 2012. It also identified how climate change, tubewell density and other physical and socio-economic factors affected the supply reliability of groundwater irrigation. Since the sample of this study covers the major provinces in both Northern and Southern China, it can be treated as being nationally representative, and the results may have some general implications for China.

Our analysis indicated that over the past 30 years (1981–2010), the annual temperature reflected an obvious increasing trend, but the change of annual precipitation was not as clear. On average, 70 percent of villages were solely dependent on groundwater for irrigation, and the other 30 percent of villages used both groundwater and surface water in their irrigation systems. The number of tubewells showed an upward trend from 2010 to 2012, and the density of shallow tubewells was greater than that of deep tubewells. The differences across provinces, whether according to irrigation source, or number or density of tubewells, were remarkable. On average, the supply reliability was 89 percent over the period from 2010 to 2012. According to farmers' responses, the main reasons for unreliable groundwater irrigation were threefold: the water table was too low (this was the most important reason), tubewells were not maintained in a timely manner and the number of tubewells in their village was simply not enough to meet their irrigation needs.

Econometric results showed that the 30-year annual temperature significantly influenced the supply reliability of groundwater irrigation, and presented a non-linear relationship. Importantly, increasing the 30-year annual temperature reduces the supply reliability of groundwater irrigation in most regions in China. When the temperature rises above the turning point (6.3°C), it changes from a positive to negative relationship with the supply reliability of groundwater irrigation. The 30-year annual temperature in eight of the nine sample provinces (i.e. except for Jilin) was higher than the turning point. If the temperature increases by 2°C in the future, with other factors remaining constant, the supply reliability of groundwater irrigation will reduce by 20 percent. In contrast, when precipitation increases by 10 percent, the supply reliability of groundwater irrigation could increase by only 3 percent; however, reducing precipitation by 10 percent decreases supply reliability by 3 percent. The significant relationship between the main climate variables (temperature and precipitation) and the supply reliability of groundwater irrigation is also consistent with farmers' responses. Climate variables significantly influence groundwater recharge as well as the groundwater table. This explains why farmers considered a low water table as the most important factor affecting their irrigation resources. Therefore, measures to improve farmers' adaptive capacities and mitigate the negative impacts of climate change on the supply reliability of groundwater irrigation need urgent attention.

Finally, increasing tubewell density greatly benefits the supply reliability of groundwater irrigation. In addition, the supply reliability of groundwater irrigation improves from increasing the density of deep rather than shallow tubewells. These results explain why farmers invest in tubewells to ensure the irrigation requirements of crops, and in sinking deeper tubewells to deal with the decline in the groundwater table (Wang *et al.*, 2009). Supporting tubewell development not only benefits farmers but is also one of the important policy options for ensuring food security and mitigating the negative impacts of drought in China over the past several decades. However, while increasing the density of tubewells may yield enough groundwater for irrigation, this approach is based on a narrow perspective and raises sustainability concerns that need to be addressed. In the long run, an overabundance of tubewells will result in further overexploitation of groundwater and create new and more profound problems. The strategy of developing tubewells to improve the adaptation capacity of the agricultural sector under the pressure of climate change will result in a decline in groundwater supply reliability in the future. The tradeoff with the resultant negative environmental issues needs to be carefully considered. The question of how policy makers can balance the number of tubewells with sustainable development of groundwater resources in the long term is beyond the scope of this study. We therefore encourage further research on this topic.

Notes

1. Not all villages used groundwater for irrigation in all three years (2010–2012); for example, in 2010, 134 villages used groundwater for irrigation, and this number was 141 in 2011 and 139 in 2012. Therefore, the final samples used in analysis for three years are 414 villages.
2. We ask village leaders the following question: In your village, when crops need groundwater irrigation, how much percentage of irrigated crop-sown areas that could not get sufficient and timely groundwater supply during 2010–2012? Based on this information, we can get indicator of the supply unreliability of groundwater irrigation (share of irrigated crop-sown areas having access to an unreliable groundwater supply), then using 1 to minus this number and we can get the indicator of the supply reliability of groundwater irrigation.
3. In order to get information about major reasons that result in unreliable groundwater irrigation supply, we asked the following questions for village leaders: In your village, what are the main reasons that result in the insufficient and untimely groundwater irrigation water supply during 2010–2012? (1 = water table is too low; 2 = the tubewell has not been maintained in time; 3 = not enough tubewells; 4 = others).
4. The full sample was subjected to a Durbin–Wu–Hausman (DWH) test for possible endogeneity in both shallow and deep tubewell densities. First, two regressions were run for shallow and deep tubewell densities. The independent variables in these two regressions are the same as those in Equation (1) (except for shallow or deep tubewell density). Second, the random errors of these two regressions were added to Equation (1), and a new regression was run. The results show that the t-statistical values of random errors in the regressions of shallow and deep tubewell densities are 0.33 and 0.32, respectively, both lower than the critical value of the t-test at 10 percent (1.65); their F-statistical value is 1.43, lower than the critical value of the F-test at 10 percent (1.60). Such results indicate that there is no significant correlation between tubewell density (both shallow and deep) and the random error of Equation (1) (Column 1 of Table IV). Therefore, one can confirm that both shallow and deep tubewell densities are two exogenous variables.

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Appendix

Province	County	Township	Village
Hebei	3	7	18
Henan	3	9	24
Shandong	3	8	22
Jilin	3	9	22
Anhui	3	9	27
Jiangsu	1	2	5
Jiangxi	4	7	9
Guangdong	3	5	8
Yunnan	3	4	7
Total	26	60	142

Source: Authors' survey

Table AI. Sample distribution of this study

	Mean	Min.	Max.	SD
Dependent variable				
Percentage of irrigated crop-sown area having reliable groundwater supply for irrigation	0.89	0.09	1.00	0.16
Independent variable				
Climate variables				
Annual temperature (°C)	13.17	2.67	22.34	4.43
Annual temperature squared	193	7.11	498.88	106.38
Annual precipitation (mm)	789	400	2,055	407
Annual precipitation squared	7,88,645	1,59,646	42,22,917	9,56,556
Tubewell density				
Deep tubewell density (number/ha)	0.07	0.00	0.69	0.10
Shallow tubewell density (number/ha)	0.10	0.00	0.69	0.13
Village characteristics				
Whether irrigating by surface water (1 = yes; 0 = no)	0.53	0.00	1.00	0.50
Landform (1 = plain; 0 = mountain)	0.07	0.00	1.00	0.25
Per capita cultivated land area (ha)	0.16	0.03	0.65	0.14
Whether having continuous residential areas (1 = yes; 0 = no)	0.59	0.00	1.00	0.49

Note: All samples are 414

Table AII. Descriptive statistics of major variables

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