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Whether climatic factors influence the frequency of punctual on-demand deliveries of groundwater for irrigation? Empirical study in the North China Plain

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Abstract

Using household level and plot level survey data spanning over 10 years, this study examines the effects of climatic factors on the frequency of punctual on-demand deliveries of groundwater for irrigation at the farm level in the North China Plain. Data show that for the past few decades, farmers have experienced a decline in the frequency of punctual on-demand deliveries of groundwater for irrigation, which is measured by the proportion of the number of groundwater irrigations whose delivery timing matched the requests of farmers. Econometric estimation results show that both long-term climate conditions (mean temperature and total precipitation) and short-term weather conditions during the growing seasons have statistically significant effects on the frequency of punctual on-demand deliveries of groundwater for irrigation. However, these effects can show opposite results. The frequency of punctual on-demand deliveries of groundwater for irrigation is negatively associated with an increase in the long-term average temperature but is positively associated with a short-term temperature rise. The effects, moreover, may also differ in magnitude. Although the frequency of punctual on-demand deliveries of groundwater for irrigation is positively associated with higher precipitation levels in both the short-term and the long-term, the latter exerts a larger influence.

Keywords Frequency of punctual on-demand deliveries of groundwater for irrigation · Temperature · Precipitation · North China Plain

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1 Introduction

The North China Plain (NCP) is a major agricultural production region in China. It produces 56% of the nation's wheat and 27% of its maize (NBSC 2013).[1] Water is alarmingly scarce in the NCP. Indeed, water availability per capita is only approximately one-sixth of the national average (Wang et al. 2015). In the past 20 years, the annual runoff has decreased by 41% in the Haihe River Basin, which is the major river basin and water catchment area in the NCP (SDRC, MWR, and MOC, 2007). Because of the declining surface water resources, farmers in the NCP rely mainly on groundwater irrigation for agricultural production (Wang et al. 2005). Currently, almost 70% of the irrigated areas depend on groundwater for irrigation. Groundwater is being pumped at rates far greater than the recharge rates. Heavy groundwater pumping in the NCP has resulted in rapid groundwater overdraft, as well as having adverse environmental effects, such as land surface subsidence, seawater intrusion, streamflow depletion, and wetland and ecological damage (Famiglietti 2014).

In addition to being threatened by water shortages, NCP agricultural production is also threatened by climate change. The mean annual temperature has increased at a rate of 0.3 °C per decade over the past 60 years (1951–2011), while the annual precipitation has declined at a rate between -2.8 and -34.3 mm per decade (Wang et al. 2015). A decline of 3.3 to 54.8 kg ha^{-1} yr^{-1} of the wheat yield and 6.6 to 15.3 kg ha^{-1} yr^{-1} of the maize yield may be attributed to climate change (Li et al. 2016; Guo et al. 2014). In addition to having a direct effect on crop yields, climate change also indirectly affects crop production through its effects on water supply. Wang et al. (2013) found that climate change is likely to reduce the agricultural water supply and shrink irrigable areas in the major river basins in northern China. Cao and Wang (2009) found that lower precipitation levels contribute significantly to the decline in groundwater levels in the NCP. However, no study has examined whether climate change has affected the frequency of punctual on-demand deliveries of groundwater for irrigation in the region. Understanding this issue can assist policymakers as they design more suitable adaptation measures to mitigate the negative impacts of climate risk.

Using unique survey data containing detailed irrigation information at the plot level, this study measures the frequency of punctual on-demand deliveries of groundwater for irrigation at the farm level and identifies its influencing factors. The key factors of interest are the climatic conditions. We pay special attention to the influence of long-term climate and short-term weather conditions. This study makes several contributions to the literature. First, the data allow us to construct a measure of the actual frequency of punctual on-demand deliveries of groundwater for irrigation at the farm level and to record fluctuations over time. Because of the lack of data, few studies employ these measures. Since farm households are the major end users of irrigation services, analyzing the actual frequency of punctual on-demand deliveries of groundwater for irrigation at the farm level will help policymakers provide more useful guidance. Second, this study quantifies the impact of climate factors, taking into account the socioeconomic environment where this impact takes place.

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[1] The NCP is located in the northern region of China and covers two metropolises (Beijing and Tianjin) and five provinces (Anhui, Hebei, Henan, Jiangsu, and Shandong) (Li et al. 2015).

2 Literature review

The punctuality of on-demand deliveries of irrigation water refer to whether the timing of the water delivery matches the crop growth demands and farmers' expectations, and as a key dimension of irrigation performance, it needs to be closely monitored and managed (Svendsen and Small 1990; Makadho 1996; Vandersypen et al. 2006; Madhava Chandran et al. 2016). Water that is delivered at the wrong times can be wasteful and even harmful to crop growth. Together with the amount of water applied during the crop season, the punctuality of on-demand deliveries of irrigation water can explain a large portion of the variations in agricultural production (Meinzen-Dick 1995).

Despite its importance, most indicators employed in the existing literature do not measure the actual frequency of punctual on-demand deliveries of irrigation water that farmers experience on their farms. Most studies assess the punctuality of on-demand deliveries of irrigation water by examining how well the timing of irrigation deliveries meets crop water requirements, often calculated by utilizing water-balance models such as FAO CROPWAT (Meinzen-Dick 1995; Makadho 1996; Vandersypen et al. 2006). However, such an approach does not account for the deviations experienced in the actual on-farm irrigation performance from what is predicted by the models (Lorite et al. 2004); it also does not consider whether the timing of irrigation deliveries is consistent with farmers' expectations. For example, levels of the frequency of punctual on-demand deliveries of irrigation water can vary among farmers sharing the same irrigation canal because of differences in their locations along the irrigation canal or the management skills of the canal operators and farmers. The frequency of punctual on-demand deliveries of irrigation water can also vary due to differences in the soil types or the slopes of the fields, which may result in different crop water requirements. Since farmers are the main end users of irrigation services and their past experiences with the level of the frequency of punctual on-demand deliveries of irrigation water influence their production decisions, measuring the actual frequency of punctual on-demand deliveries of irrigation water at the farm level is essential.

Partly because of a lack of data, most studies do not quantify the effects of factors that could influence the frequency of punctual on-demand deliveries of irrigation water. Previous studies have reported the potential influence of a large set of factors, such as the availability of water facilities, the features of water facilities (e.g., system design, operation, and maintenance), characteristics of communities (e.g., institutional capacity), characteristics of farmers (e.g., irrigation experience) and the characteristics of farms (e.g., soil type and location within the irrigation scheme and field and farm size), and climate conditions (Lorite et al. 2004; Cheng and Wang 2008; García-Bolaños et al. 2011; Mangrio et al. 2014). However, few studies have provided empirical evidence concerning whether these factors can, in fact, explain the frequency of punctual on-demand deliveries of irrigation water. The lack of quantitative evidence limits the usefulness of most studies in helping policymakers determine where to focus their efforts to improve the frequency of punctual on-demand deliveries of irrigation water.

So far, little attention has been paid to the frequency of punctual on-demand deliveries of irrigation water in the literature on groundwater economics. For the purposes of this study, four reasons exist to focus on groundwater irrigation. First, in the agricultural sector, where most water use is consumptive, groundwater irrigation is becoming increasingly important for its absolute value and its share in the total available irrigation supply (Siebert et al. 2010). Second, the most vulnerable group of farmers is more likely to bear most of the impacts from changes in groundwater irrigation. Indeed, in many parts of the world—such as South Asia and North

Africa—poor farmers with small farms rely on groundwater for irrigation (Siebert et al. 2010). Third, irrigation is often considered as a main adaptation strategy to climate change, and groundwater irrigation is often considered more reliable than surface water irrigation. However, declining levels have become a global crisis (Famiglietti 2014). With the decrease in groundwater levels, access to groundwater irrigation water has become an increasingly important issue. Many households without their own tube wells have to buy irrigation services from groundwater markets to gain access to irrigation water (Zhang et al. 2008). Therefore, tracking the frequency of punctual on-demand deliveries of groundwater for irrigation as an indicator of both irrigation performance and the health of aquifers is more important now than ever to water managers. This information will help policymakers assess whether groundwater irrigation can be an adequate climate change adaptation strategy. Finally, groundwater use mainly depends on the characteristics of local aquifers and their interaction with the local surface water system (Fleckenstein et al. 2010).[2] As we will demonstrate, a better understanding of the extent of the impact of climate factors on the frequency of punctual on-demand deliveries of groundwater for irrigation can be obtained by using specific local information for the analysis, as we have done herein by focusing on the NCP region.

3 Data and descriptive statistics

3.1 Data

All socioeconomic data used in this study come from the China Water Institutions and Management survey (CWIM). The CWIM data were collected in four rounds in 2001, 2004, 2007, and 2011. The survey was carried out in the Hebei, Henan, and Ningxia provinces. Since groundwater irrigation is virtually nonexistent in Ningxia, only data from Hebei and Henan are used in this study. Both provinces are highly dependent on groundwater irrigation (Zhang et al. 2008). During the survey, a stratified random sampling strategy was used to select the sample villages. The strata are defined based on water availability. For example, villages in the Hebei Province were chosen from counties closer to the coast (the most water-scarce area of the province), closer to the mountains (the most water-abundant areas), and between those two areas. In Henan Province, villages were chosen from counties in irrigation districts at varying distances from the Yellow River (Zhang et al. 2008).

Farmers and village leaders from each village were interviewed, and separate questionnaires were used for each group of respondents. Between four and six farm households were randomly selected. In each sample village, the investigators asked the village leaders to provide a list of names of all the household heads. The first household was selected randomly, and the other households were selected according to the calculated interval distance (total number of households/number of households to be selected). The same households were tracked during the four rounds of CWIM. Some sample attrition occurred. Most often, this attrition was due to the inability to track some households because they migrated to other

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[2] For example, aquifers in the NCP are divided into four layers (Huang et al. 2013; Su et al. 2014). The first layer (less than 60 m thick) is an unconfined aquifer. The second layer (60 m thick) is a shallow semi-confined aquifer. Fresh water and brackish water coexist in these two aquifers. Both the third layer (more than 90 m thick) and the fourth layer (50 m to 60 m thick) are confined aquifers containing fresh groundwater (Su et al. 2014). Some villages in the NCP pump groundwater from deep confined aquifers while others do so from unconfined or semi-confined aquifers where more groundwater-surface water interactions occur (Huang et al. 2013).

places for off-farm work. In the statistical analysis, off-farm work is included as an explanatory variable to control for attrition bias. In villages with sample attrition, replacement households were randomly selected so that at least four households were interviewed in each village. In the third round of the survey, eight new villages (and 32 new households) were added to the Hebei Province sample. These were also surveyed in the fourth round. During the four rounds, the CWIM survey covered 329 households across 56 villages in Hebei and Henan provinces. A total of 146 households were monitored during all four rounds of the survey, and 62 households were missing during one or more rounds of the follow-up surveys. Within each household, two plots were selected to collect detailed information on crop production and irrigation activities. Wheat and maize are the major crops grown in the area. The growing season of maize largely overlaps with the rainy season in the NCP (June to October). As a result, maize is not as heavily irrigated as wheat. The final sample used in this study contains 249 wheat-planting households from 49 villages in 10 counties within Hebei and Henan provinces. The final sample for the empirical analysis contains information on 772 wheat plots.

Data on the county-level monthly mean temperature and monthly total precipitation from 1960 to 2012 are obtained from the Chinese National Meteorological Information Center. These climate variables are constructed based on actual measurements from 753 national meteorological stations located throughout China (Wang et al. 2009). Since only two of the ten sample counties have their own meteorological stations, spatial interpolation is used to generate the temperature and precipitation data for the other eight sample counties (Li and Heap 2014). Thornton et al. (1997) method of spatial interpolation is used. This method is based on the spatial convolution of a truncated Gaussian weighting filter with the set of station locations. Using climate data from meteorological stations and soil data from the Institute of Soil Science at the Chinese Academy of Sciences, monthly Palmer Drought Severity Indices (PDSIs) are calculated based on a method developed by Liu et al. (2004). PDSI is the most prominent and widely used drought index (Palmer 1965). This index incorporates antecedent and current moisture supply and demand figures into a hydrological accounting system. Its values range from approximately − 10 (dry) to + 10 (wet). A value between − 3 and − 3.9 indicates severe drought and a value of − 4.0 or less indicates extreme drought (Dai 2011). Spatial interpolation is also used to generate PDSIs for the sample counties without meteorological stations.

The growing season for winter wheat in the sample areas is from October of 1 year until June of the next year. Monthly mean temperatures during the growing season are used for generating variables in this study since the growth of winter wheat is mainly influenced by temperature fluctuations during the growing season. Because precipitation outside the growing season could influence crop growth through mechanisms such as soil moisture accumulation, the annual total precipitation is also used for generating variables. The total annual precipitation is calculated as the total precipitation from July of the previous year to June of the current year. In the empirical analysis, both historical and contemporaneous climate variables are used. The long-term climate variables mainly measure the climatic conditions of a region, and following common practice in the literature (e.g., Di Falco and Veronesi 2013; Zhang et al. 2016), a period of 30 years (1981–2010) is used to study the influence of historical climate factors.

Our data have some limitations. The survey data provide a relatively small sample size over a small geographical area. A maximum of six households per village were sampled, and only two sample provinces were included. Increasing the number of sample households per village could allow us to explore the heterogeneity among farmers. Increasing the geographical coverage of the sample would also capture more variations in climate and weather conditions.

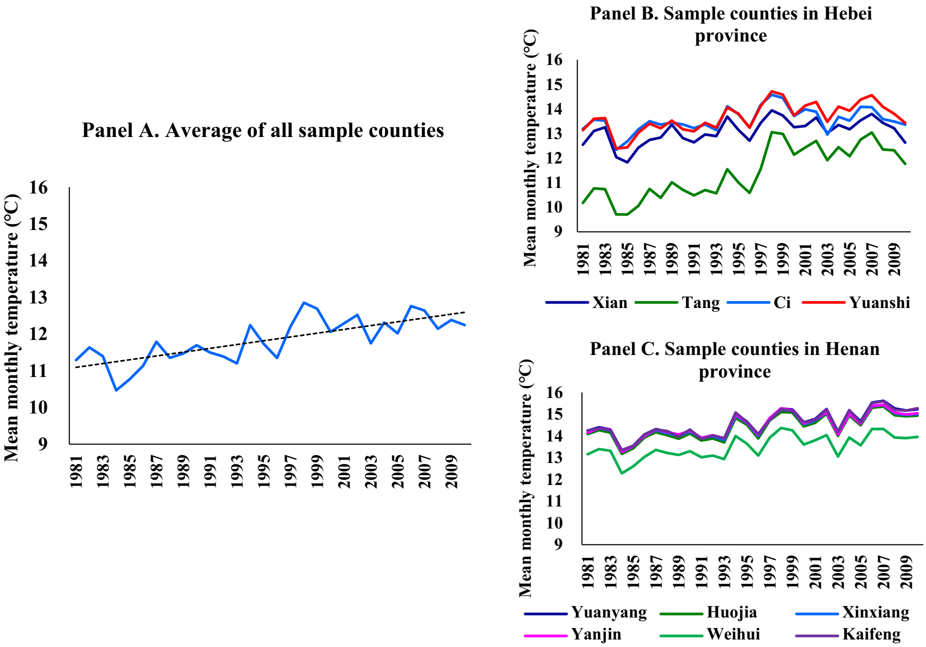
Therefore, the continued collection of survey data is important so that further research can be conducted. In addition, inclusion of other measures of the frequency of punctual on-demand deliveries of groundwater for irrigation at the plot level in future surveys will improve the understanding of the impact of climate conditions. Finally, we have not considered the relationship between climate change and migration, and its potential influence on the frequency of punctual on-demand deliveries of groundwater for irrigation. In the past few years, although their relationship has attracted the interest of some researchers, the results are contradictory (Perch-Nielsen et al. 2008; Warner et al. 2010; Black et al. 2011; Pei 2013; Grecequet et al. 2017). In addition, even if climate change forced some farmers in the study area to move elsewhere, thereby causing sample attrition, the impact of climate on the frequency of punctual on-demand deliveries of groundwater for irrigation could potentially be underestimated. In this case, the main conclusion of this study will nevertheless hold.

3.2 Changes in climatic factors and the frequency of punctual on-demand deliveries of groundwater for irrigation

Despite the significant number of fluctuations, the mean monthly temperatures in the sample area displayed a clear warming trend over the past 30 years (1981–2010). The average mean monthly temperature for all sample counties was 11.29 °C in 1981 and increased to 12.25 °C by 2010 (Fig. 1a). Moreover, the rate of increase varied among the counties in Hebei Province (Fig. 1b). For example, the mean monthly temperatures in Xian County exhibited a warming of 0.09 °C over the past 30 years. In contrast, Tang County experienced a rise of 1.59 °C during the same period (Fig. 1b). Compared with Hebei Province, the pattern of change in mean monthly temperatures was more homogeneous among the six sample counties in Henan Province (Fig. 1c). The mean monthly temperatures showed an overall increasing trend over the past 30 years, with a slight decline in the 1980s but with a clear rising trend since the 1990s.

Unlike the mean monthly temperatures, the annual total precipitation in the sample area exhibited neither an increasing nor a decreasing trend during the sample period (Fig. 2a). No significant change in precipitation levels is observed in any county during the period (Fig. 2b, c). Additionally, variations in precipitation are dominated by year-to-year fluctuations. The standard deviation of annual total precipitation is 72 mm over the past 30 years, which is 16% of the mean. Over the years, a slight reduction in drought stress was observed in the sample provinces, leading to an increase in the PDSI (Fig. 3a). The increase is more visible in the Hebei Province, which has experienced less drought stress since 2002 (Fig. 3b). This trend is consistent with findings of recent studies such as Liu et al. (2013), who found extreme droughts have become less frequent over the past 50 years.

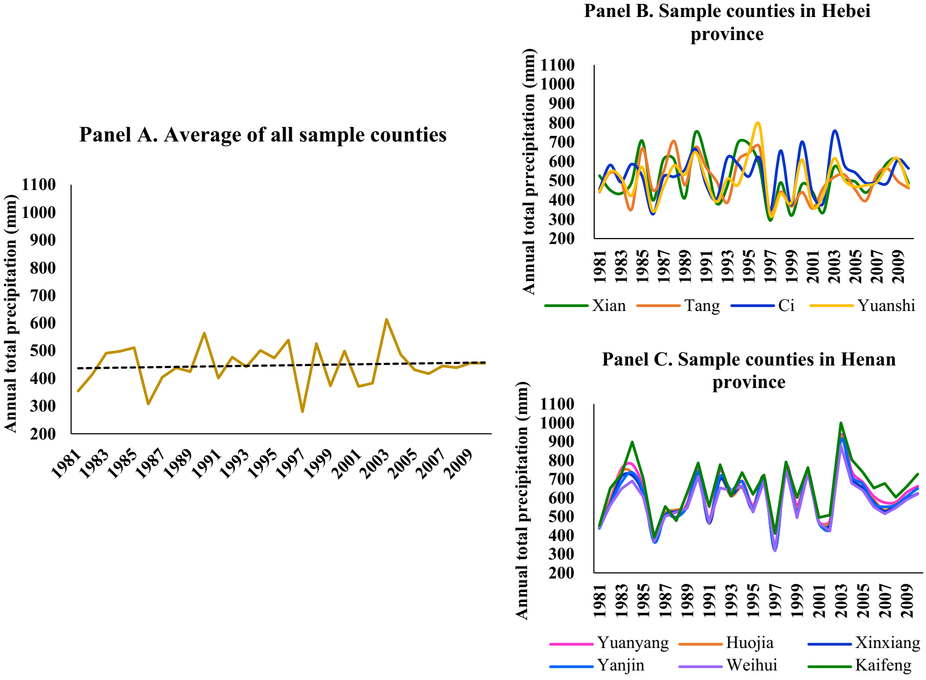
Since in rural China, groundwater is usually delivered at the requests of farmers instead of according to a fixed schedule, it is a type of on-demand delivery. Farmers often determine the need and the timing for groundwater irrigation based on plant status and field conditions such as soil moisture, observed rainfall levels and past experience. The on-demand groundwater delivery is considered punctual if groundwater is delivered at the time requested by famers. Otherwise it is delayed. During the survey, for each plot survey, farmers reported the total number of times wheat was irrigated and how many times the on-demand delivery was delayed. Following Karamouz et al. (2013), the relative frequency of punctual on-demand deliveries of groundwater for irrigation is defined as:


Panel A. Average of all sample counties

Panel B. Sample counties in Hebei province

Panel C. Sample counties in Henan province

Fig. 1 Mean monthly temperatures in sample areas (1981–2010)


Panel A. Average of all sample counties

Panel B. Sample counties in Hebei province

Panel C. Sample counties in Henan province

Fig. 2 Annual total precipitation in sample areas (1981–2010)

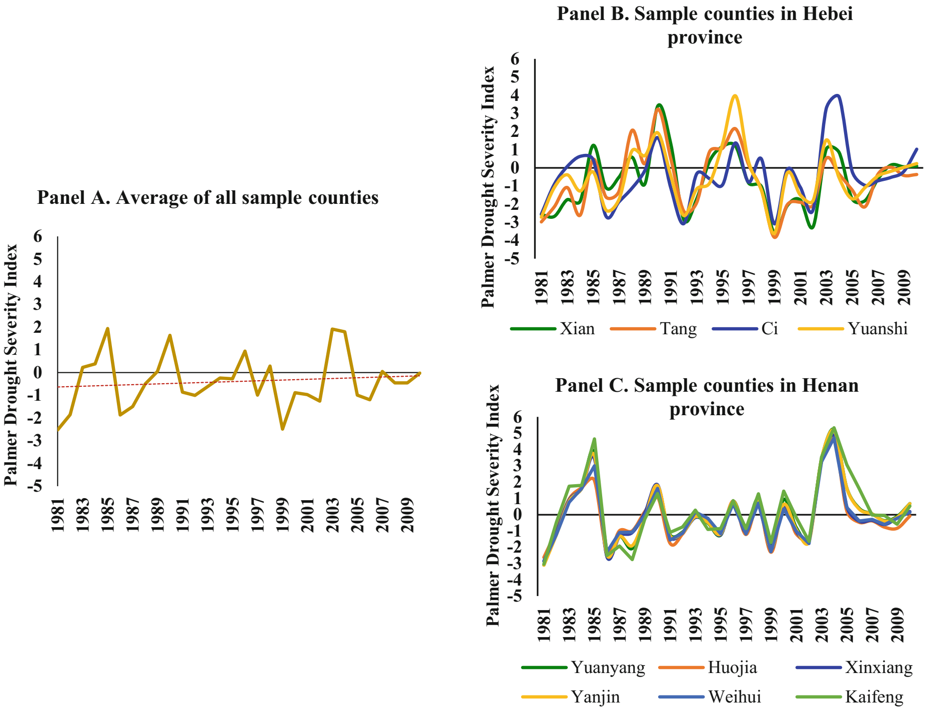


Fig. 3 Palmer Drought Severity Index in sample areas (1981–2010)

$$R = n_{\text{punctual}}/n_{\text{total}} \tag{1}$$

where R is the frequency of punctual on-demand deliveries of groundwater for irrigation (hereafter briefed as the frequency of punctual on-demand deliveries), n_{punctual} is the number of groundwater irrigations whose delivery timing matched the requests of farmers, and n_{total} is the total number of groundwater irrigations during the growing season.

The results show that farmers experienced a decline in the frequency of punctual on-demand deliveries from 2001 to 2011. On average, the number of times the sampled wheat plots were irrigated during the growing season decreased from four in 2001 to three in 2011 (Table 1).[3] Naturally, not all farmers had the same irrigation times in each year. Specifically, in 2001, most wheat plots (78.3% of plots) were irrigated four times by farmers, whereas some farmers chose to irrigate more frequently (9.5% of the plots) or less frequently (12.2% of the plots) than four times. By 2011, the farmers' most frequent choice of irrigation times was three times (42.5% of plots). In addition, some plots were irrigated twice (29.0%), whereas others were irrigated fewer than two times (6.3%) or more than three times (22.2%). In 2001, an average of 3.6 irrigations was supplied on time (column 2, row 1). Using Eq. 1, the frequency of punctual on-demand deliveries was 0.91 (column 3, row 1). By 2011, this frequency had fallen to 0.87 (column 3, row 4).

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[3] Reduced irrigation times may also be one aspect of the picture on the effect of climate on groundwater irrigation (Wang et al. 2019), but this is not the focus of this study. This study focuses on how the frequency of punctual on-demand deliveries is affected by climate.

Table 1 The frequency of punctual on-demand deliveries of groundwater for irrigation on wheat plots in the NCP for 2001, 2004, 2007, and 2011

	(1) Total number of groundwater irrigations during the growing season	(2) Number of groundwater irrigations whose delivery timing matched the requests of farmers	(3) [a]The frequency of punctual on-demand deliveries of groundwater for irrigation
2001	4	3.64	0.91
2004	3	2.66	0.89
2007	3	2.66	0.89
2011	3	2.60	0.87

[a] Column (3) = Column (2)/Column (1)

During the survey, farmers were asked to report the reasons for the unpunctual groundwater deliveries for irrigation. In 2011, the most cited reason was low groundwater levels (unpunctual deliveries occurred for 56.4% of wheat plots), which resulted in lower water yields or dried-up tube wells (Table 2, column 5, row 1). However, in 2001, delays in the groundwater deliveries for this reason affected only 12.9% of the wheat plots. In 2001, the most important reason for unpunctual groundwater deliveries was the failure of the tube wells or pumps (48.4% of wheat plots, column 4).[4] This finding is consistent with our data analysis showing that the average groundwater level in the sample villages dropped from 18.6 m in 2001 to 30.5 m in 2011. The second most cited reason in 2011 and 2001 was the lack of a sufficient number of tube wells to provide irrigation services for all farmers at the peak of the irrigation season, implying increasing demands for groundwater irrigation. Finally, electricity shortages were also an important reason for unpunctual groundwater deliveries in 2001, affecting 12.9% of the wheat plots. By 2011, this effect did not exist, which reflected the general improvements in electricity supply over the decade.

4 Econometric models

Based on the descriptive analysis above and previous studies concerning the potential factors influencing the punctuality of on-demand deliveries of irrigation water (Lorite et al. 2004; Cheng and Wang 2008; García-Bolaños et al. 2011; Mangrio et al. 2014), the following econometric model is specified for quantifying the effects of climate factors and other factors

Table 2 Most reported reasons for unpunctual groundwater irrigation on wheat plots

	Share of plots (%)			
	2001	2004	2007	2011
Low groundwater level	12.9	25.8	44.9	56.4
Insufficient number of tubewells	16.1	48.4	40.8	38.5
Dysfunctional tubewells or pumps	48.4	12.9	8.2	2.6
Unsatisfactory service provided by tubewell operators	9.7	6.5	4.1	2.6
Electricity shortage	12.9	6.5	2.0	0.0

If groundwater is not delivered at the time requested by famers, the groundwater delivery is considered unpunctual on the frequency of punctual on-demand deliveries:

$$R_{ijkct} = a + c'_{ct}\theta + z'_{ijkct}\beta + \mu P + \varepsilon_{ijkct} \tag{2}$$

where R_{ijkct} is the frequency of punctual on-demand deliveries on plot i of household j in village k of county c in year t. As seen in Eq. 1, R_{ijkct} is calculated as the portion of the number of groundwater irrigations whose delivery timing matched the requests of farmers and is always positive and bounded between 0 and 1. In such a case, ordinary least squares estimation could generate coefficients with a downward bias (Wooldridge 2002). To avoid such bias, we apply the Tobit model to estimate Eq. 2 β via maximum likelihood estimation.

The key variables of interest are the climatic factors in vector c'_{ct}. Three groups of climatic factors are included: (i) long-term climatic factors, measured by mean monthly temperatures during the growing season and annual total precipitation over the previous 30 years (1981–2010) (i.e., historical temperature and precipitation); (ii) short-term weather conditions, measured by mean monthly temperature and annual total precipitation for the survey years (2001, 2004, 2007, and 2011); and (iii) historical and short-term drought stress, measured by the PDSI during the corresponding periods. For groups (i) and (ii), interaction terms for temperature and precipitation are also added. These interaction terms are used to reveal that the effect of temperature may depend on precipitation and vice versa and to determine the potential effect of one weather variable given the effect of the other weather variable (Blanc 2012). Significant interaction effects of temperature and precipitation are found on root production, root mortality, mean standing crop, community structure and composition, and crop yields (Bai et al. 2010; Blanc 2012; Hou et al. 2013).

The vector z'_{ijkct} contains several groups of factors that may affect the frequency of punctual on-demand deliveries. The first group of variables measures village characteristics, including tube well density and the proportion of deep tube wells in the village. During the survey, village leaders reported the total number of tube wells and the total cultivated area in the village. Tube well density is then calculated as the number of tube wells per unit of cultivated area. Our sample areas have deep tube wells that usually draw water from confined aquifers and shallow tube wells that draw water from unconfined/shallow aquifers without an overlying aquitard. The depth at which a tube well is considered “deep” varies from village to village because of differences in hydrogeological structure. This information was provided by staff members of the local water resources bureau and by village leaders. Village leaders were also asked to report the number of deep tube wells and the number of shallow tube wells. Their answers are used to calculate the proportion of deep tube wells in the village.

The second group of variables measures household characteristics, including farm size, total number of plots, age, and level of education of the household head. The allocation of labor between farm and off-farm work is measured by the percentage of household labor time spent on off-farm work. The third group measures plot characteristics, including groundwater access methods, means of water conveyance, distance from a plot to the farmer’s house, and distance from a plot to the water outlet of the tube well that supplies groundwater to the plot. During the survey, farmers were asked how they accessed groundwater for the irrigation of each plot. Two dummy variables are constructed to indicate the groundwater access method (from the groundwater market, collective tube wells, or the farm’s own tube wells). The first dummy variable equals 1 if farmers irrigated their plots using water purchased from the groundwater market. In rural China, farmers often purchase groundwater from fellow farmers who have tube wells (Zhang et al. 2008). The second dummy variable equals 1 if farmers irrigated their plots using water delivered from collective tube wells. Often village leaders make all decisions regarding collective wells (whether to sink wells, how much water to pump, and so on). Village leaders often hire managers to operate tube wells and allocate groundwater under their supervision. Plots that farmers irrigated using water from their own tube wells constitute the base group (where both dummy variables equal 0). Farmers were also asked to report the total distance between a plot and the water outlet of the tube well that supplied groundwater to the plot and the means of conveyance (surface pipes, underground pipes, lined canals, and/or mud canals). In the case where multiple means were used, farmers also reported the fraction of the conveyance distance for each method. The method of water conveyance is measured as a proportion of the total conveyance distance that used surface pipes, underground pipes, or lined canals (in contrast to mud canals that would incur much larger seepage losses).

The vector $z_{ijkct}^{'}$ also includes the village-level cluster variance. Farmer irrigation behavior may be highly correlated within the same village, but it is more likely not to be correlated with irrigation behavior in the different villages. Therefore, the cluster variance at the village level is controlled to account for intragroup autocorrelation.

The dummy variable P equals 1 for sample plots in Henan Province (fixed effects at the Province level). This variable captures the effects of any province-specific factors that do not change over time. Year dummies are not included because they are highly collinear with the climate variables. The error term ε_{ijkct} has a mean of zero. Summary statistics of the variables are reported in Appendix Table 4.

5 Estimation results

Table 3 reports results from two specifications of Eq. 2. The first specification excludes the drought variables (column 1), and the second specification includes them (column 2). It is likely that temperature and precipitation can capture most of the variations in weather conditions that are predicted by drought occurrences (Yu and Babcock 2010). Therefore, the inclusion of drought variables in a specification that already includes temperature and precipitation may not be necessary. However, the occurrences of droughts may bring about changes in water resources that are not predicted by changes in temperature or precipitation (Boubacar 2010; Attavanich and McCarl 2011; Ahmed and Schmitz 2011; Blanc 2012). To test the sensitivity of the estimation results of Eq. 2 to the drought variables, both specifications are estimated. The estimation results do not differ much between the two specifications. When the influences of temperature and precipitation are controlled, the frequency of punctual on-demand deliveries is not significantly influenced by the PDSI, indicating that the influence of temperature and precipitation captured most of the effect of climate on the punctual on-demand deliveries of groundwater. The estimated coefficients of all other climate variables are largely consistent in terms of signs, sizes, and levels of statistical significance. Importantly, Table 3 does not report variable coefficients, but instead, it reports the marginal effects of each variable considered.

5.1 Impacts of long-term climatic factors

The estimation of Eq. 2 shows that historical temperature is likely to have a significant influence on the frequency of punctual on-demand deliveries (Table 3). The estimated

Table 3 Factors that influence the frequency of punctual on-demand deliveries of groundwater for irrigation at the plot level

Dependent variable: the frequency of punctual on-demand deliveries of groundwater for irrigation	(1)	(2)
Climate variable[a]		
Historical mean temperature	1.3360**	1.3506**
	(2.30)	(2.35)
Historical total precipitation	0.0291**	0.0293**
	(2.17)	(2.24)
Historical mean temperature *historical total precipitation	−0.0027**	−0.0027**
	(2.31)	(2.37)
Survey-year mean temperature	−0.3421***	−0.3416***
	(3.52)	(4.19)
Survey-year total precipitation	−0.0066***	−0.0066***
	(3.43)	(4.31)
Survey-year mean temperature *survey-year total precipitation	0.0007***	0.0007***
	(3.72)	(4.57)
Historical drought index		0.0228
		(0.07)
Survey year drought index		0.0021
		(0.14)
Village characteristics		
Number of tube wells per hectare	0.0355	0.0346
	(0.93)	(0.86)
Proportion of deep tube wells (%)	0.0003	0.0003
	(0.54)	(0.56)
Household characteristics		
Farm size (ha)	0.0227	0.0243
	(0.40)	(0.41)
Total number of plots	−0.0101*	−0.0100*
	(1.96)	(1.95)
Age of household head	−0.0005	−0.0006
	(0.38)	(0.41)
Years of schooling of household head	0.0018	0.0018
	(0.37)	(0.37)
Percentage of household labor time spent on off-farm work	0.0006	0.0006
	(0.91)	(0.87)
Plot characteristics		
Water purchased from groundwater markets (1 = yes; 0 = no)	−0.0581*	−0.0590*
	(1.88)	(1.83)
Water delivered from collective tube wells (1 = yes; 0 = no)	−0.0015	−0.0020
	(0.04)	(0.05)
Proportion of pipe and lined canal (%)	−0.0002	−0.0002
	(0.54)	(0.52)
Distance to house (km)	−0.0305**	−0.0301**
	(2.18)	(2.12)
Distance to water outlet (km)	−0.0073	−0.0074
	(0.25)	(0.25)
Province dummy, = 1 if Henan province	0.0054	0.0051
	(0.04)	(0.03)
Constant	−54.9392*	−55.3922*
	(1.65)	(1.68)
Observations	772	772
Pseudo R^2	0.1599	0.1600

Absolute value of *t* statistics are reported in parentheses; *, **, and *** denote levels of statistical significance at 10%, 5%, and 1%, respectively

[a] Historical climate variables are averaged over the classical period of 30 years (1981-2010). Survey years refer to 2001, 2004, 2007 and 2011

coefficients of historical mean temperatures are positive and statistically significant. The estimated coefficients of the interaction term between historical temperatures and precipitation are negative and statistically significant, indicating that the effect of the temperature will vary with the precipitation level. Eq. 2 can be rewritten as $E[R_{ijkct}] = \theta_1 T + \theta_2 T \times P + Q$, where E is the expectation operator, T is the historical mean temperature, P is the historical total precipitation, and Θ contains all the terms in Eq. 2 that do not contain T. Then, the marginal effect of historical mean temperature is $\partial E[R_{ijkct}]/\partial T = \theta_1 + \theta_2 P$. Under different levels of historical total precipitation, the marginal effect[5] of historical mean temperature on the frequency of punctual on-demand deliveries is illustrated in Fig. 4a, which is based on the regression results in column 1 of Table 3. Figure 4a shows that, at higher levels of long-term precipitation, increases in long-term temperature have a larger negative effect on the frequency of punctual on-demand deliveries, suggesting that the rise in long-term temperature has a greater impact on the frequency of punctual on-demand deliveries in relatively wet areas. This may be because, in relatively wet areas, farmers rely more heavily on precipitation, and they often look forward to rainfall rather than irrigation when drought stress occurs. If T and P are evaluated at their respective sample means (10.24 °C and 566.35 mm), the marginal effect of the historical mean temperature is -0.18 (using the coefficients in columns 1 and 2). This means that, if the historical mean temperature were to increase by 0.1 °C, the frequency of punctual on-demand deliveries would decrease by 0.02. One possible mechanism for the negative effect is the effects of long-term temperature on several aspects of water balance, including recharge, evaporation, transpiration, and leaf area index (McCallum et al. 2010). An increase in temperature would increase evaporation and transpiration, resulting in the crop growth requiring more water, which may lead to more frequent irrigation. Meanwhile, an increase in temperature can lead to reduced groundwater recharge by decreasing the downward water flux below the root zone (Liu 2011). With a reduced groundwater stock resulting from lower recharge rates, providing punctual groundwater irrigation to satisfy farmer demand for larger quantities of water and more frequent irrigation, as well as meeting the demands from an increased number of farmers, is challenging.

The frequency of punctual on-demand deliveries is also influenced by historical total precipitation. The marginal effect of historical total precipitation at different levels of the historical mean temperature is calculated by applying the same method used to calculate the marginal effect of historical mean temperatures, and the results of this calculation are illustrated in Fig. 4b (using the coefficient estimates in column 1 of Table 3). The negative interaction effect between long-term precipitation and temperature is also shown in Fig. 4b, although most of the confidence intervals contain zero. This indicates that the positive effect of historical total precipitation on the frequency of punctual on-demand deliveries will diminish if it is accompanied by rising long-term temperature. If T and P are evaluated at their respective sample means, the marginal effect of historical total precipitation is 0.0017 when the coefficients of column 1 in Table 3 are used. The marginal effect is 0.0016 when using the coefficients in column 2 of Table 3. Therefore, if precipitation increases by 10 mm and all other factors remain constant, the frequency of punctual on-demand deliveries will increase by 0.02. One possible explanation is that an increase in the long-term precipitation level will directly translate into an increase in soil moisture and groundwater recharge (Calow and Macdonald 2009). As a result of reduced irrigation water requirements

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[5] Because the values of the frequency of punctual on-demand deliveries are between 0 and 1 and many of them are, in fact, equal to 1, the marginal effects of climatic variables are computed for the dependent variable conditional on the right-censoring limit.

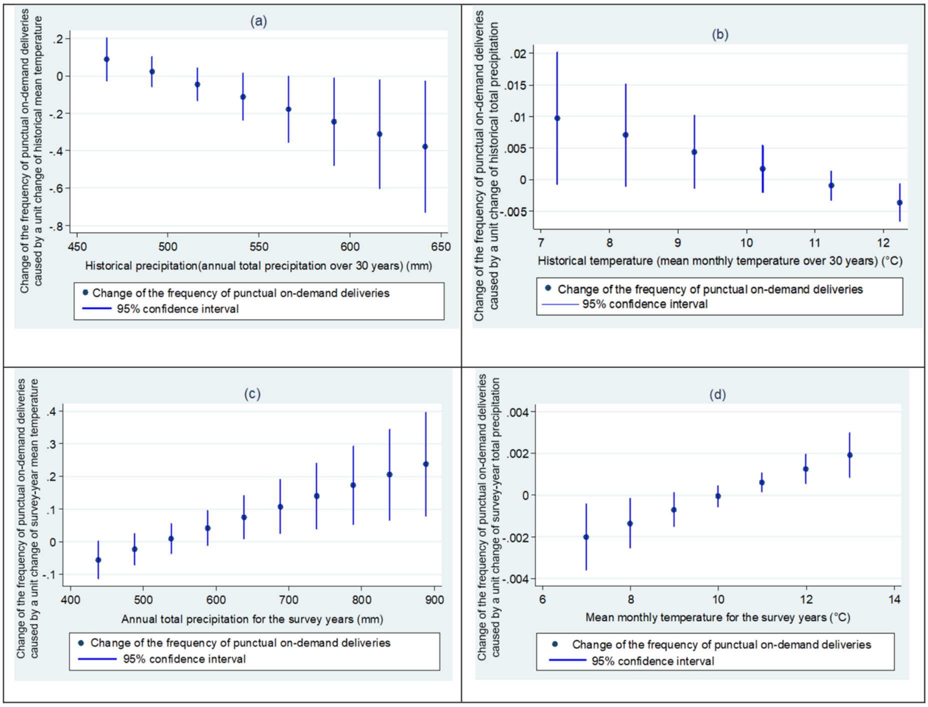

Fig. 4 Marginal effects of temperature and precipitation on the frequency of punctual on-demand deliveries of groundwater for irrigation. Note: 1) Marginal effect of temperature on the frequency of punctual on-demand deliveries of groundwater for irrigation means that the change of the frequency of punctual on-demand deliveries caused by a unit change of historical (**a**) or survey-year (**c**) mean temperature;2) Marginal effect of precipitation on the frequency of punctual on-demand deliveries of groundwater for irrigation means that the change of the frequency of punctual on-demand deliveries caused by a unit change of historical (**b**) or survey-year (**d**) total precipitation;3) The 30 years refer to years from 1981 to 2010, and the survey years refer to 2001, 2004, 2007, and 2011.

and increased groundwater supply, farmers are more likely to get punctual groundwater deliveries for irrigation at their requests.

5.2 The impact of short-term weather conditions

Evidence also indicates that short-term weather conditions affect the frequency of punctual on-demand deliveries. Our results reveal that the estimated coefficients of mean temperature and total precipitation in the survey year are statistically significant at the 1% level (Table 3). The estimated coefficient of their interaction term is also statistically significant. The positive interaction effect of short-term temperature and precipitation is illustrated by the marginal effect graphs in Fig. 4c and d. By using the coefficients of column 1 or column 2 in Table 3, the marginal effect of the mean temperature in the survey year, which is calculated at the sample mean, is 0.07. In other words, ceteris paribus, a 0.1 °C increase in mean temperature during the wheat growing season leads to an increase of approximately 0.01 in the frequency of punctual on-demand deliveries. This result is interesting and contrary to the effect of a rise in the long-term temperature. A change in the short-term temperature, on the other hand, does not have an immediate effect on the groundwater supply. However, when observing a high temperature in the short-term, farmers may be more proactive in making sure irrigation is done in a punctual way to mitigate/prevent yield losses because of drier conditions. In contrast, farmers may be less responsive to changes in long-term temperatures since these changes are less obvious to them. The marginal effect of total precipitation in the survey year is 0.0006, which means the frequency of punctual on-demand deliveries will increase by 0.006 when the total precipitation of the survey year increases by 10 mm. This effect is consistent with the direction of the marginal effect of long-term precipitation, although it is significantly smaller in magnitude. This may be because recharge is the main channel through which climate affects groundwater supply, and long-term precipitation may play a more important role (Zhang et al. 2006; Fishman et al. 2011). For example, the aquifers in Hebei Province are recharged by the much slower horizontal flows from mountain areas. In contrast, short-term precipitation brings immediate relief to dry weather conditions, which probably reduces the perceived need for punctual groundwater irrigation. The findings are similar if the coefficients in column 2 of Table 3 are used.

5.3 The impact of socioeconomic factors

The estimated results concerning other control variables are also of interest. For example, the estimated coefficients of the dummy variables corresponding to buying water from groundwater markets are negative and statistically significant at the 5% level for both specifications (Table 3). The frequency of punctual on-demand deliveries is reduced by approximately 0.06 on wheat plots irrigated using water purchased from groundwater markets when compared with those irrigated using water from the farmer’s own tube wells. This reduction may be because tube well owners often only provide extra groundwater irrigation capacity to buyers after meeting their own needs. The estimated coefficient of the total number of plots is negative and statistically significant in both specifications. This means households with more plots are more likely to experience unpunctual groundwater irrigation. This unpunctual groundwater irrigation is probably because a larger number of plots increase the complexity of irrigation management in terms of both quantity and scheduling. Consequently, households with more plots may find it more difficult to ensure that all plots are irrigated in a punctual manner during the irrigation season. The estimated coefficients of the variable measuring distance to home are negative and statistically significant at the 5% level, implying that plots further away from home are less likely to be irrigated in a punctual way. This may be because it is more time-consuming and inconvenient for farmers to irrigate plots far from home in a punctual manner.

6 Conclusions

Over the past few decades, a rising temperature trend coupled with more volatile precipitation and a slight reduction in drought stress have been observed in the NCP. In the context of these climate changes, farmers have experienced a decline in the frequency of punctual on-demand deliveries, measured by the proportion of the number of groundwater irrigations whose delivery timing matched the requests of farmers. Econometric estimation results show that both long-term climate conditions (mean temperature and total precipitation) and short-term weather conditions during growing seasons have statistically significant effects on the frequency of punctual on-demand deliveries. However, their effects may occur in opposite directions. The frequency of punctual on-demand deliveries is negatively associated with an increase in the long-term average temperature but is positively associated with a short-term temperature rise. These effects can also differ in magnitude.

Although the frequency of punctual on-demand deliveries is positively associated with higher precipitation levels in both the short-term and the long-term, the latter exerts a larger influence.

Our findings have important implications for the NCP, where climate change and water management are currently two of the most important policy challenges. Our results show that groundwater irrigation does not completely protect farmers from varying climate factors. For example, the warming trend in the long-term is likely to reduce the frequency of punctual on-demand deliveries. Temperature is projected to continue to rise, and precipitation is projected to show large fluctuations in the NCP throughout the 21st century (China Meteorological News 2013). Therefore, groundwater management policies need to account for the effects of climate factors on the performance of groundwater irrigation—including whether groundwater is delivered at the time requested by famers—and integrate adaptive management into policy design. Particularly, lower groundwater levels—which can be partly attributed to changes in climate—have been cited as the main reason for delayed groundwater irrigation in the area in recent years. Therefore, groundwater development should be combined with strategies to help improve irrigation performance. For example, on-farm water storage facilities, such as ponds or community reservoirs, can store water from irrigation runoff or precipitation for later use when groundwater supplies are insufficient. Building recharge facilities in suitable areas will also boost the frequency of timely groundwater delivery for irrigation.

Previous studies provide evidence that farmers in the NCP are using groundwater markets as a strategy to adapt to climate change by applying less irrigation to achieve the same yield (Zhang et al. 2016). However, this study suggests that groundwater markets may negatively affect the frequency of punctual on-demand deliveries. Based on field observations, this negative effect is likely to be related to the informal nature of groundwater markets in rural China, where appropriate governance is lacking (Zhang et al. 2008). Farmers buy and sell water without any written contracts, and oral commitments cannot be adjudicated in a court of law. The groundwater markets are also local in nature, meaning that most buyers and sellers are farmers in the same villages who grow similar crops and therefore have similar water demands in terms of quantity and timing. This reduces the potential of groundwater markets to assist water users in addressing fluctuations in water demands because of climate change. Therefore, to improve the adaptive capacity of the NCP economy to inevitable climate change and water shortages, policymakers should aim to shape the development of groundwater markets to mitigate these negative consequences. For example, encouraging more transparent transactions and implementing a monitoring mechanism could improve the operation of groundwater markets. Policies that develop groundwater markets between villages and different sectors, for instance agricultural and industrial sectors, may also be useful.

Importantly, other climate factors, such as relative humidity, light, and wind speed, may have an effect on the frequency of punctual on-demand deliveries. They are not considered in this study but would represent an interesting topic for further research. Moreover, future research could also attempt to determine the effects of the frequency of punctual on-demand deliveries on other aspects, such as irrigated acreage, crop mix, crop yield, and farmer income, for example. In addition, incorporating findings from studies that use hydrological models to link climate change to groundwater supply in the NCP would shed more light on the mechanism by which climate factors can influence the punctual deliveries of groundwater for irrigation.

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Appendix

Table 4 Summary statistics of the variables

	Mean	Std. Dev.	Min.	Max.
Dependent variable				
The frequency of punctual on-demand deliveries of groundwater for irrigation	0.89	0.26	0.00	1.00
Independent variables				
Climate variables				
Historical mean temperature (°C)	10.24	1.09	7.52	11.17
Historical total precipitation (mm)	566.35	54.47	499.51	648.32
Survey-year mean temperature (°C)	10.99	1.27	7.88	12.96
Survey-year total precipitation (mm)	638.43	123.34	455.65	885.36
Village characteristics				
Number of tube wells per hectare	0.37	0.40	0.01	2.75
Proportion of deep tube wells (%)	26.54	38.83	0.00	100.00
Household characteristics				
Farm size (ha)	0.49	0.27	0.05	2.00
Total number of plots	4.15	3.05	1.00	25.00
Age of household head (years)	49.35	10.21	25.00	77.00
Years of schooling of household head	6.99	2.94	0.00	15.00
Percentage of household labor time spent on off-farm work	19.66	17.10	0.00	76.67
Plot characteristics				
Water purchased from groundwater markets (1=yes; 0=no)	0.17	0.38	0.00	1.00
Water delivered from collective tube wells (1=yes; 0=no)	0.64	0.48	0.00	1.00
Proportion of pipe and lined canal (%)	58.36	48.73	0.00	100.00
Distance to house (km)	0.76	0.78	0.00	4.00
Distance to water outlet (km)	0.17	0.36	0.00	6.00

Number of observation is 772

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