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Estimation of Irrigation Water Demand and Economic Returns of Water in Zhangye Basin

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Abstract: The objective of this study is to provide estimates of price elasticities of irrigation water demands in Zhangye Basin (ZB), an inland river basin in China, with the most recent data and to compare the values of marginal product (VMPs) of water to the prices of water farmers are currently paying. With a set of village and household survey data collected in 2009 and 2014, household fixed effects models are used to estimate water demand and crop production functions. The estimation results are then used to estimate price elasticities and VMPs. Results show that demands for surface water, groundwater, and conjunctive irrigation water are all in the inelastic range. The results imply that water prices may need to be increased significantly to induce sizable water savings. Another significant finding is that for a large share of the sample households, VMPs of water are higher than the prices of water. The estimated VMPs provide policy makers with some guidelines on the minimum level of water prices required to achieve any water savings among those households.

Keywords: surface water; groundwater; conjunctive irrigation; price elasticity; value of marginal product of water; Zhangye Basin; Heihe River Basin

1. Introduction

Agriculture is the largest user of water in many parts of the world [1]. This is particularly true in inland river basins where agriculture faces less competition for water from industry or residential sectors due to a lower degree of industrialization and a smaller population. For example, nationwide agriculture used 62.4% of water in China in 2016 [2]. However, in Zhangye Basin (ZB), which is located in inland northwest China, more than 90% of water is used for crop irrigation [3]. Therefore, irrigation water is the focus of water resources management in many inland river basins. Often, one of the management goals is to reduce the volume of water used in agricultural production.

Although concerns of water shortages have been ongoing for decades, policy makers are still in search of effective policy instruments to induce water conservation or to improve water use efficiency. In recent years, policy makers have turned their attention from supply-side approaches such as building reservoirs or lining canals to water demand management [4]. Most countries have been promoting more efficient irrigation technologies and best management practices [5]. More recent literature, however, has identified unintended consequences of more efficient irrigation technologies. For example, although a more efficient irrigation technology may cut down irrigation application rates, farmers may also increase irrigated acreage or switch to more water-intensive crops now that the effective price of water is lower [6]. FAO (Food and Agriculture Organization of the United Nations) [7] shows that in the MENA region (the Near East and North Africa), the promotion of more efficient irrigation technologies has increased the overexploitation of groundwater resources. Huang et al. [8], however, argue that more efficient irrigation technologies may have the potential to reduce water use in rural China because the small farm size in that region limits the unintended consequence of the expansion of irrigated acreage. Their study did not find evidence that farmers change crop mix after the use of more efficient irrigation technologies. Market-based solutions such as water rights trading and water markets hold great potential for improving the allocative efficiency of water use [9]. Some regions including ZB have also implemented water use quota at the level of irrigation districts or basins [10].

Increasing water price is also back on the agenda of some countries, including China [11]. Irrigation water pricing policy may be particularly suitable for rural China. China's irrigation water users are characterized by millions of small farms that are less than half a hectare [12]. The peculiar nature of this water use will ensure that the transaction costs of water rights trading easily outweigh the potential benefits. Since groundwater use is largely unregulated in rural China, a quota on water use is not feasible in areas where groundwater is the main source of irrigation water. In contrast, since the cost of groundwater is largely the energy cost of pumping it out, the price of groundwater can be influenced by the government through the price of energy [4]. Partly in preparation for reforming prices of surface water, China's government has implemented many irrigation projects that installed water measurement equipment along canals that deliver water to rural villages [13,14]. China's experience from past reforms also indicates that rural households respond to economic incentives [15]. Increasing water price can provide the economic incentive for households to cut their water use.

Knowledge of water demand is the key information needed in designing a water pricing policy. A vast body of literature exists that provides estimates of the price elasticity of irrigation water demand in various parts of the world. The meta-analysis of 24 studies reported in the United States between 1963 and 2004 shows an average price elasticity of −0.48 [16]. Irrigation water demand in other countries such as Australia and Tanzania are also found to be inelastic [17,18]. Studies that report crop-specific estimates have the same finding of inelastic water demand. For instance, the estimated price elasticities of demand for water used in wheat production ranges from −0.12 to −0.03 [19–21]; those for maize fall between −0.67 and −0.04 [22–24]. Similar to other parts of the world, irrigation water demands in China are also not responsive to small changes in water prices [25–27]. For example, using household cross section data from ZB, Zhou et al. [28] estimated the price elasticity of irrigation water demand was about −0.55. Unfortunately, not many empirical studies have focused on inland river basins.

The main reason for the inelastic demand is the low price of water most agricultural users are paying. In ZB, water is priced at between 10% and 90% of the cost of supplying water [29,30]. When prices are set at the lower end, demand for most goods would be in the inelastic range. Huang et al. [4] also find that some farmers in Hebei province, located in north China, face a gap between the cost of groundwater they pay and the value of groundwater. The latter is measured as the increment in crop income if one more unit of groundwater were available. In regions outside China such as the United States [31], India [32,33], Spain [34], and Tunisia [35], prices of water used to irrigate various crops are also found to be below the economic returns of water. If water is priced below the returns it can generate in agricultural production, then farmers will not respond to a rise in the water price until it climbs to the level of water value. One of the reasons to observe water prices that are below the economic returns of water is that farmers face constraints in quantities of available water. In this case, unless water price is lifted to the level of economic returns, farmers will use up all the available water and will not respond to a rise in the water price.

There is a consensus among researchers that the price of irrigation water needs to be increased significantly to induce sizable water savings [4,33–38]. In areas where policy makers are considering pricing policy, the pertinent question is how much the price of water needs to be raised to achieve the intended amount of water savings. To answer this question, policy makers need to understand both the price elasticity of water demand and the value of water. Discussions of policies that increase water prices should always consider the political economy of the region [39–41]. In the context of China, after trying out other policy instruments such as promoting water saving technologies and tradable water rights, policy makers renewed their efforts to reform irrigation water price [13,14]. Agricultural water resource fees have been suggested for both surface water and groundwater in some western provinces since 2014. Another key component is tiered pricing: a relatively low water price up to a base amount (quota) and then a much higher price for any amount in excess of quota [13,14]. Recognizing that these changes in water prices are likely to increase irrigation costs, the government also implements complementary policies that compensate for farmers' income losses. One example is a subsidy that is based on land size and automatically given to any farmers that grow grain [14]. The objective of this study is to provide such estimates for ZB, a typical inland river basin in China. Several previous studies have touched on the same issues in ZB. For example, using a bio-economic model and simulations, Shi et al. [42] have found farmers' irrigation water demand is not sensitive to changes in water price, because the shadow price of agricultural water is much higher than the cost of water farmers are paying. Tian et al. [43] argue that there is still room for increasing the price of irrigation water in ZB based on the level of crop income farmers can generate from irrigation. Neither study, however, uses empirical data that represent actual water use behaviour of rural households. Therefore, their findings may be driven by assumptions embedded in their models or argument.

Unlike previous studies, this study is based on a set of household data collected in multiple irrigation districts (IDs) in ZB. The sample of villages is a representative sample of the whole basin. The data allow us to estimate a separate water demand for farmers that grow different crops and for farmers that use different sources of irrigation water (groundwater, surface water, or conjunctive use). Taking into account the heterogeneity in water demand is important, because the economic value of irrigation water depends on types of crops as well as sources of irrigation supply. For instance, the value of marginal product of irrigation water in Hebei Province in North China is about 0.71 yuan per m^3 for wheat and 0.54 yuan per m^3 for corn [4]. It also depends on the source of irrigation water supply. The economic returns of irrigation water in cotton production is 0.36 yuan per m^3 on plots irrigated by surface water and 0.48 yuan per m^3 on plots irrigated conjunctively by surface water and groundwater [31]. Second, the survey has collected information on a large set of factors that may influence input uses in agricultural production, especially water use. This helps us control for many confounding factors and thus avoid omitted variable bias. To our knowledge, this study is among the very few that provides crop-specific empirical estimates of values of irrigation water using household survey data.

The rest of the paper is organized as follows. The second section describes the study region and the survey data. The third section presents the econometric model used to estimate the irrigation water demand and reports estimated price elasticities. The fourth section imputes the economic returns of irrigation water using estimation results of crop-specific production functions and then discusses findings on the water price and economic returns of water. The final section concludes and draws policy implications.

2. Study Region and Data

2.1. Description of Study Sites

Heihe River is China's second largest interior river. It originates from the Qilian Mountains in Qinghai province, passes through Gansu province, and ends in East Juyanhai Lake in Inner Mongolia (Figure 1). Heihe River Basin (HRB) is divided into upstream, midstream, and downstream by two hydrological stations (Yingluoxia and Zhengyixia). The historical mean annual precipitation declines sharply from approximately 338 mm in the upstream, 127 mm in the middle stream, and 49 mm in the downstream; about 77% of the rainfall are concentrated between June and September, with an annual potential evapotranspiration of 2400–3000 mm (China Meteorological Administration). There is relatively sufficient water upstream, but it is scarce in the other two areas, especially downstream.

Hills dominate the terrains in the upstream, and animal husbandry is the main income source for farmers. In contrast, the river's lower reaches contains mostly deserts. The midstream consists of broad, flat plains suitable for irrigated agriculture, in which water use accounts for the majority of total water consumption in the river basin (about 94%), which is located in the center of the "One Belt and One Road" and "Silk Roads" economic belts [44]. The major economic sector in the midstream that uses water in the HRB is irrigation agriculture, in which spring-wheat and maize are the main crop types.

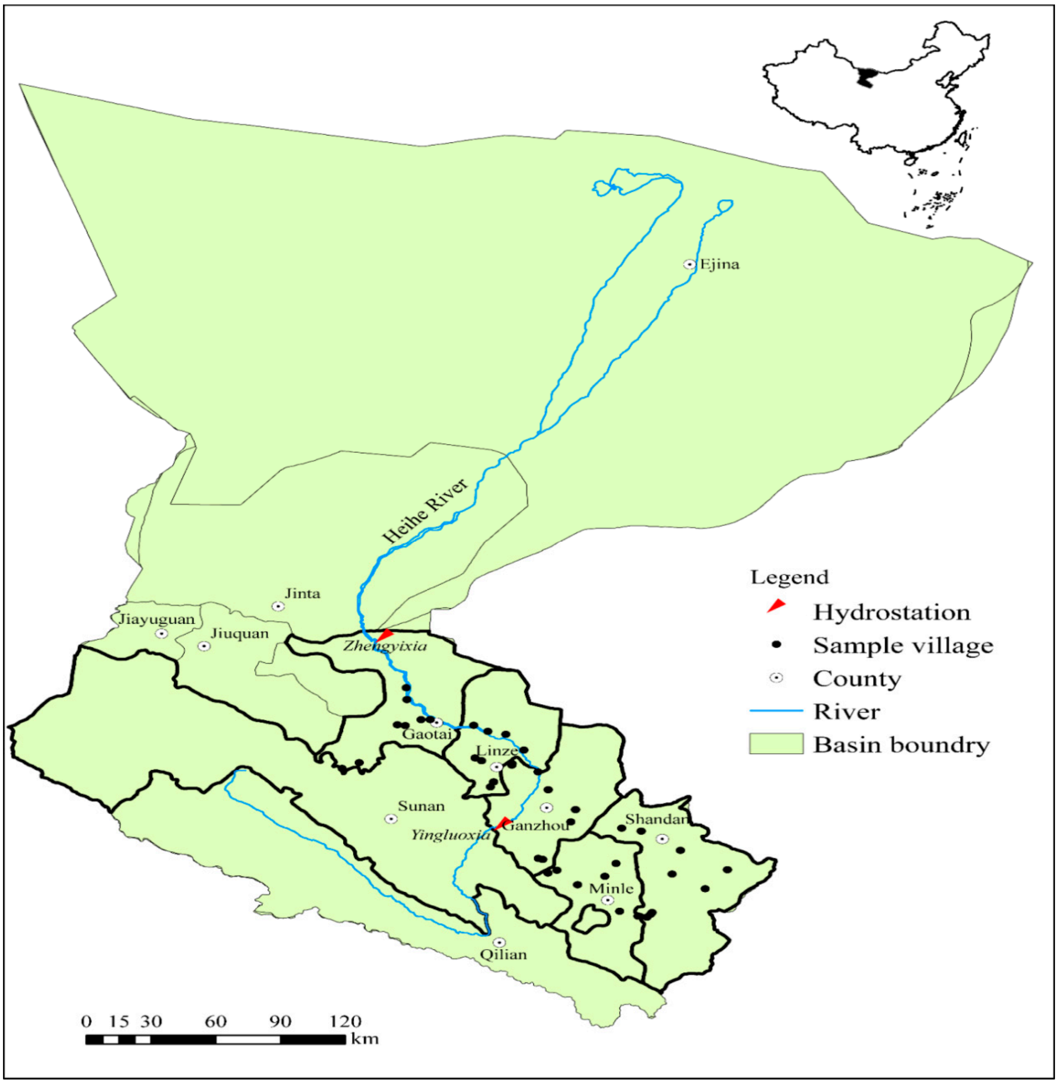

Figure 1. Study region and sample villages.

Zhangye is located in the midstream of the HRB. The water availability in Zhangye is only 1250 m^3 per capita per year or 7950 m^3 per hectare per year, which are only 60% and 30% of the national average, respectively [45,46]. The agricultural sector in Zhangye is the key sector, whose sowing area is close to 270,000 ha, and water consumption accounts for 89% of the total water use [47]. Surface water supplies about 67% of the irrigation water and the rest comes from groundwater (Zhangye Water Authority). Due to the lack of rainfall and runoff water, groundwater is used excessively in ZB for irrigation, which results in rapid increase of the depth of the ground water there at a rate of 0.5–1.8 m each year [44,48]. However, there is an irrigation water balance, because there are strong interactions among surface, ground, river, and irrigation water [49]. The interactions between surface water and groundwater occur in the both river domain and irrigated farm lands, and the latter is recharged by the infiltrated irrigation water, which enables farmers to extract groundwater as the supplementary irrigation water source [3]. This study area covers Zhangye's four counties (Linze, Gaotai, Minle, and Shandan) and one urban district (Ganzhou).

In Zhangye, there is a specific procedure for distributing surface water. Zhangye earmarks limited overall water for various uses according to the circumstances of the population and development of industries. Then, the amount of agricultural water is dispensed to each county in line with the status of their water resources and water rights area. Later, the agricultural water of each county is further distributed to each irrigation district according to the same principle. Lastly, irrigation districts, with the assistance of water user associations (WUA), apportion agricultural water to each farm household based on their water rights area and irrigation quota, which can restrict the maximum water consumption of a household during a period of time (a year or an irrigation cycle). Groundwater is the supplementary water source for irrigation in some areas where there is no surface water resource or water facilities. Irrigation wells there are usually drilled by village or a group of farmers, so the groundwater is distributed among all the investors.

2.2. Survey Data

The data came from the two rounds of surveys conducted by the authors in our study area above in 2009 and 2014. There was an ID in each township of all counties; we randomly chose four townships from each county. We adopted a stratified sampling approach to select villages, which means that we randomly chose two villages based on a census of villages in the upper and lower reaches of a main canal within an ID, respectively (Figure 1). In each village, we randomly selected four farm households. After obtaining the basic information about each household's plot, we chose two plots from each household for more careful investigation.

In the 2009 round, 40 village leaders, 40 irrigation channel managers, 55 well managers, and 160 farm households were interviewed with separate survey questionnaire for each group of respondents. The household survey gathered detailed information about crop production and irrigation management on 320 plots. Among the 160 households, 109 remained in the 2014 round. The high attrition rate of 32% is common in any household survey conducted in rural China. The main reason for the attrition is that some households moved away to work on off-farm jobs. The attribution rate is higher at the plot level. Among the 320 plots in the 2009 sample, no more than 200 plots remained the 2014 rounds. Some plots were lost to land transfers or highway construction. In the crop level regressions, more plots were lost due to changes in the type of crop grown. Due to the high attrition rate, in the empirical analysis, the data were treated as an unbalanced panel data on the household level. In the 2014 round, 47 new households were added. In total, the final sample used in the empirical analysis includes 196 wheat plots and 122 maize plots. The new households are also included in the empirical analysis. A regression is run to see if attrition is correlated with the key variables of interest and the prices of irrigation water. The dependent variable is a dummy variable that equals one if an observation is dropped out of the sample in the second round of the survey. The result indicates that the price of irrigation water does not predict attrition. A variable that measures the share of off-farm labor in the household is also added to control for any attrition bias.

Surface water is main irrigation source in our survey, while groundwater takes up a relatively small share of water use. In rural China, surface water is usually the preferred source of irrigation water, because surface water is significantly cheaper than groundwater in most areas. So, most households would prefer surface water if it were available. The availability of surface water is determined by the presence of canals and the availability of water from the irrigation districts, both of which are out of the control of individual households. Therefore, the choice of using surface water or groundwater is largely exogenous. In most villages, households either all use groundwater, or all use surface water. In villages in which both surface water and groundwater are available, there are some variations in the type of irrigation water used within the village. For instance, in the sample plots where wheat and maize were grown, the shares of plots only irrigating surface water were 60% and 43%, respectively (Table 1). In contrast, the shares of plots only irrigating groundwater for both crops were no more than 28% during these years. The remaining plots used both surface and groundwater, which occupied only 13% for wheat and 35% for maize.

Table 1. Share of sample plots by sources of irrigation water in Zhangye, Heihe River Basin (%).

Irrigation Sources	Full Sample	2008	2014
Wheat			
Surface water	60	58	62
Groundwater	27	26	28
Conjunctive irrigation	13	16	9
Maize			
Surface water	43	12	56
Groundwater	21	26	19
Conjunctive irrigation	35	62	25

Source: Authors' survey.

In order to estimate the price elasticity of irrigation water demand and its economic value, we designed three separate survey instruments: one for farmers, one for irrigation managers (including managers of irrigation channels and wells), and one for village leaders. In our survey, we recorded the output, inputs, and the corresponding prices of each crop in a plot. Information on plot level irrigation application rates was also collected during the survey. For each crop, households reported the length of irrigating time and the total number of irrigations during the entire growing season. For irrigation application rates, households reported both the volume of water applied per irrigation in cubic meters and the depth of application in inches. The same set of questions were also used in the village leaders and water managers (well operators and canal managers) questionnaires.

For plots irrigated by groundwater, if households were not clear about the volume of water applied, we obtained information from the manager of the well from which the household obtained the water. The managers usually were able to give us detailed information about the size of the irrigation pump and the average volume of water that each pump lifted out of the wells per hour. Most households knew how long the pumps were operated to irrigate their plots, since the length of time determined their groundwater payment. We then calculated the volume of water by multiplying the average volume of water pumped per hour by the length of irrigating time.

For surface water plots, most households were not able to report the volume of water applied in cubic meters. However, most of them could report the length of irrigation time and/or the depth of application in inches. If the depth of application is known, the application rate is calculated as the product of plot area and the depth of application. If the length of irrigation time is known, the application rate is calculated as the product of irrigation time and flow rates in the canals. The flow rates in the canals were obtained from canal managers and county water resource bureau officials. If both pieces of information were available, the average of the two application rates was used.

In addition, the water distribution system and its pricing schemes are important, which have effects on water use efficiency [50,51]. In our survey, households reported the amount of the money that they paid for irrigation water for each crop. In almost all villages, households paid for groundwater according to the number of hours that the managers operated the pumps to irrigate their crop. Therefore, the cost of groundwater is closely related to the energy cost of lifting water out of wells (either electricity or diesel). The price of electricity used in agricultural production is about 40% less than that for residential use. This subsidy applies to all agricultural electricity use, and is not tied to groundwater pumping. Moreover, the irrigation wells in Zhanye are usually owned by a group of farmers or all the farmers in a village, which also incurs management expenses that are also included in farmers' irrigation fee. In surface water area, the volume of water is measured where water is diverted from branch canals managed by irrigation districts into a village. The payment the village makes to the irrigation district is calculated based on the volume of water diverted. Within the village, however, the volume of water is not measured when it is delivered to farmers' plots. Farmers pay for water on a per unit of land basis. About 75% of villages collected the surface water fee by area, and 25% collected it by time, while all villages consumed electricity during irrigation [10]. For both groundwater and surface water, the price of water is calculated as total payment for water divided by the volume of water used. In other words, the computed water price is the marginal cost of irrigation in each plot.

Moreover, as the result of variations of management fee for channels or wells, volumetric price from irrigation districts, and electricity price of various wells, the final water prices for both surface water and groundwater varied at village level. Specifically, for surface water, its prices in different irrigation districts were not consistent, which made water price vary at village level, and the diverse fee of channel management in different villages enlarged the variations. For ground water, the electricity price and management fee in different villages also varied a lot, which made variations of groundwater price occur at village level. However, there were also some small variations within villages for groundwater price. In our sample area, some respondents pumped water out of their own wells, while others purchased water from others that owned wells (informal groundwater markets) or had water delivered from collectively owned wells [52]. The price of electricity did vary within the village, since a service charge was often added to the electricity price when households purchased water on the informal groundwater markets. To examine the sources of variation in water prices, we decomposed water prices' variations between and within villages, which indicates the variation in the price of water was mainly due to regional differences among villages, not from within villages (Appendix A, in which we also decomposed variation for other key variables in the same way).

Besides the above, we collected information on climate and the characteristics of each plot, household, and village. For climate data, we adopted temperature and precipitation in crops' growth season on the county level. Household attributes included the age and education level of the household head, and the share of off-farm labor and fixed assets value in a family; plot features included soil type (loam, clay, or sandy soil), the distance from water outlets to plots and their rate of lined canals, plot area, and the situation in which a plot suffered disasters (mainly drought). For the survey with village leaders, we asked village leaders to assess water scarcity in their villages, such as whether water was insufficient and the number of areas of each irrigation source.

3. Irrigation Water Demand and Its Price Elasticity

3.1. Descriptive Statistical Analysis

Irrigation application rate varies depending on crops and irrigation sources. As a whole, irrigation application rate of maize in Zhangye was much more than that of wheat, about 75% (Table 2). This is opposite to the situation in the monsoon area, where wheat use more irrigation water. In the inland river basin, which, like HRB, has little rainfall, maize relies on irrigation and uses more water than wheat, because the basic water requirement of maize is bigger than wheat. From the view of irrigation source, conjunctive irrigation consumed more water than both surface water and groundwater for wheat and maize. For instance, wheat's irrigation application rate using conjunctive irrigation was 7060 m^3 per ha, about 37% and 48% more than that of surface water and groundwater, respectively. This is due to the fact that there are better water facilities in the villages that have more plots of conjunctive irrigation, which enable farmers to gain more water when crops need it. In addition, irrigation application rate of groundwater was always the lowest for both crops.

Increasing water price reduces the irrigation application rate for both wheat and maize in all irrigation scenarios. As a whole, from the lowest quarter interval (for water price) to the highest one, the irrigation application per ha using surface water for wheat and maize declined by 53% and 34%, respectively. Likewise, for irrigation application per ha using groundwater, the rates of reduction were 8% for wheat and 41% for maize. The story in the plots under conjunctive irrigation was similar. However, the negative relationship between price and irrigation application rate is not feasible among each price quartile. For instance, it shows positive relationship between price and irrigation application rate for maize irrigated by surface water from the second to the fourth price quartile. This is because all the samples in the second price quartile belong to the year 2014, when there was more rainfall during maize's growing season, and thus irrigation application rate was relatively small.

The results above imply that irrigation source and irrigation water price can possibly affect crops' irrigation application. However, due to many other factors affecting irrigation application, such as household characteristics or regional circumstances in nature, we cannot determine the real relationship (of irrigation application to irrigation source and water price) merely by using simple descriptive statistical analysis. Therefore, multivariate econometric analysis is required to analyze the real relationship between irrigation application and irrigation source and water price.

Table 2. Irrigation application rates for crops based on diverse water prices in ZB, 2008 and 2014.

Water Price Quartiles	Full Sample		Surface Water		Groundwater		Conjunctive Irrigation	
	Mean Water Price (yuan/m^3)	Irrigation Application Rate (m^3/ha)	Mean Waterb Price (yuan/m^3)	Irrigation Application Rate (m^3/ha)	Mean Water Price (yuan/m^3)	Irrigation Application Rate (m^3/ha)	Mean Water Price (yuan/m^3)	Irrigation Application Rate (m^3/ha)
				Wheat				
1–25%	0.08	6481	0.09	6316	0.07	4833	0.07	8560
25–50%	0.13	6433	0.13	6728	0.20	5570	0.10	7705
50–75%	0.24	4595	0.24	4580	0.31	4347	0.13	7511
75–100%	0.71	3709	0.76	2993	0.78	4457	0.23	4391
Average	0.29	5305	0.30	5163	0.34	4793	0.13	7060
				Maize				
1–25%	0.06	10,617	0.07	12,417	0.03	9668	0.07	9450
25–50%	0.10	9818	0.10	7573	0.07	10,113	0.10	12,609
50–75%	0.12	9600	0.16	8040	0.10	10,075	0.13	9029
75–100%	0.32	7010	0.37	8236	0.33	5752	0.22	7720
Average	0.15	9269	0.18	9047	0.13	8994	0.13	9708

Note: Water prices are measured in 2014 yuan. Water price under conjunctive irrigation is the weighted average of surface water price and groundwater price with the weights are the volumes of surface water and groundwater used. Source: Authors' survey.

3.2. Estimation of Price Elasticities of Irrigation Water Demand

Theoretically, there are two sets of input demands that can be estimated: conditional input demand that can be derived from cost function based on Shephard's Lemma and input demand that can be derived from profit function using Hotelling's Lemma. In the context of rural China, profit maximization is more consistent with farmers' production behavior. This can be traced back to the beginning of the economic reform in the 1980s when farmers were incentivized to boost production by allowing them to claim a share of crop income generated on plots assigned to them [53–55]. This is further supported by the finding of Zhang et al. [56] that farmers are applying excessive amount of fertilizer beyond the point of profit maximization. Such behavior is inconsistent with cost minimization. Since prices of output and inputs are exogenous for farmers while crops' yields are not, farmers' goals are to maximize their profits during agricultural production rather than to minimize their costs. Hence, in the empirical analysis, the following equations are used to investigate the link between irrigation application rate and water price:

$$\ln W_{ijkt} = \boldsymbol{\alpha}_{jk,1} + \theta_1 \ln c_{ijkt} + \ln \mathbf{P}_{ijkt} \boldsymbol{\beta}_1 + \mathbf{X}_{ijkt} \boldsymbol{\delta}_1 + \nu_{ijkt,1} \quad (1)$$

$$\ln W_{ijkt} = \boldsymbol{\alpha}_{jk,2} + \theta_s \mathrm{SW}_{ijkt} \times \ln c_{ijkt} + \theta_g \mathrm{GW}_{ijkt} \times \ln c_{ijkt} + \theta_c \mathrm{Conj}_{ijkt} \times \ln c_{ijkt} + \ln \mathbf{P}_{ijkt} \boldsymbol{\beta}_2 + \mathbf{X}_{ijkt} \boldsymbol{\delta}_2 + \nu_{ijkt,2} \quad (2)$$

where W_{ijkt} is the irrigation application rate on the ith plot of jth household in kth village in year t. Here, to make results more standardized and provide an intuitive understanding, we think the results would not change much if we switch to using total water use per plot. We are estimating plot level demand for water used to irrigate the same crop (either wheat plot or maize plot). The size of plot is controlled for in the regression. In addition, farmers have very limited means to change their plot sizes, because in our sample areas they still cannot legally buy or sell land. The key variable of interest is the price of water, c_{ijkt}. Two specifications are used. In Equation (1), only c_{ijkt} is included. In Equation (2), c_{ijkt} is interacted with three dummy variables that indicate a plot is irrigated by surface water (SW), groundwater (GW), or conjunctively (Conj). Prices of output and non-water inputs such as labor are contained in the vector $\mathbf{P}_{ijkt}$. Here, the models are for single crop and the two major crops grown in Zhangye are spring wheat and maize due to factors such as the climate and soil types. These two crops are grown in two distinctive seasons that basically do not overlap in time. Therefore, switching between spring wheat and Maize is not a likely response to changes in water prices.

Four groups of variables are included in the vector $\mathbf{X}_{ijkt}$. The first group of variables controls for village characteristics. A dummy variable is used to indicate whether water resources are scarce in the village. This is constructed from answers village leaders have given to the question "Are water resources scarce to the extent that agricultural production is affected?" Two variables are included to measure the shares of village's irrigated area irrigated only by surface water and by surface water and groundwater conjunctively. The second group includes four household level variables: age and years of education of households' heads, the share of household labor engaged in off-farm employment, and the total value of house(s) owned by a household. The third group measures plot characteristics such as plot size, soil type, the distance from water outlet to plot, and the share of the distance of the lined canals. A dummy variable is also used to indicate if the plot experienced drought, which was collected when we surveyed each sample plot. In this case, the variable of drought is not likely to vary between plots within the same village, and it is defined at the village level, which can also be illustrated from Appendix A. The fourth group are variables that measure mean temperature and total precipitation in the growing season. These weather variables are only available at the county level. A year dummy variable is also included that equals one for year 2014. The year dummy can capture the general trend of policy and changes in agricultural technologies. Moreover, all the variables in the vector $\mathbf{X}_{ijkt}$ are exogenous, which cannot be influenced by water prices or irrigation application rate.

Equations (1) and (2) are estimated for wheat and maize separately. Before estimation, Hausman test is employed to determine whether household fixed effects or random effects are used. The p-values of Hausman tests using the specifications in Equations (1) and (2) of wheat equations are 0.0000. The p-values are 0.0452 and 0.0051, respectively, for maize equations. Therefore, test results indicate that fixed effects estimators should be used. In fact, the regression is carried out at the plot level. So, even though a household was only in one round, it may still stay in the regression if multiple plots from the same household are in the sample data. In Equation (1), household fixed effects (or household specific intercepts) are denoted by the vector $\boldsymbol{\alpha}_{jk,1}$. It captures any time-invariant household level characteristics. One way to operate the household fixed effects model is to lag Equation (1) by one time period, which gives Equation (3):

$$\ln W_{ijk,t-1} = \boldsymbol{\alpha}_{jk,1} + \theta_1 \ln c_{ijk,t-1} + \ln \mathbf{P}_{ijk,t-1}\boldsymbol{\beta}_1 + \mathbf{X}_{ijk,t-1}\boldsymbol{\delta}_1 + \nu_{ijk1,t-1} \quad (3)$$

Notice the lagged term of $\boldsymbol{\alpha}_{jk,1}$ is itself because it is time invariant. Subtracting Equation (3) from (1) generates Equation (4):

$$(\ln W_{ijkt} - \ln W_{ijk,t-1}) = \theta_1(\ln c_{ijkt} - \ln c_{ijk,t-1}) + (\ln \mathbf{P}_{ijkt} - \mathbf{P}_{ijk,t-1})\boldsymbol{\beta}_1 + (\mathbf{X}_{ijkt} - \mathbf{X}_{ijk,t-1})\boldsymbol{\delta}_1 + (\nu_{ijkt,1} - \nu_{ijk1,t-1}) \quad (4)$$

The term $\boldsymbol{\alpha}_{jk,1}$ disappears in Equation (4). Estimating Equation (4) thus generates consistent estimates of all parameters in Equation (1), such as θ_1, $\boldsymbol{\beta}_1$, and $\boldsymbol{\delta}_1$, without the need to include all possible observed and unobserved time-invariant factors at the household level. Household fixed effects are implemented in a similar fashion to estimate Equation (2). Robust covariance matrices that are clustered at village level at which the prices vary are calculated due to concerns of heteroscedasticity. Furthermore, our dataset is a short panel that only contains data of two years, 2009 and 2014, in which we should not worry about the problem of autocorrelation in the fixed effects [57,58]. Sampling weights are also incorporated in the estimation.

The estimations of Equations (1) and (2) performed well for both wheat and maize (Table 3). The goodness of fit measures (adjusted R^2) are above 0.8, which sit at the upper end of the range of R^2s observed in empirical analysis that use household level repeated cross sectional or longitudinal survey data [59,60]. Most estimated coefficients have expected signs and are statistically significant. For example, estimated coefficients of log of total precipitation are negative in all regressions but are only statistically significant in maize regressions. This is consistent with the fact that the growing season of maize overlaps with the rainy season in the region. Therefore, the level of precipitation will have a larger influence on the irrigation application rates on maize plots than on wheat plots. The results also indicate that after holding other factors constant, in villages with water scarcity, farmers are likely to use less water per ha to irrigate both wheat and maize. A higher share of off-farm labor in the household may reduce the irrigation application rate for maize, since most irrigation methods used in rural China such as boarder irrigation are still labor intensive. The decrease of labor for crop production associated with off-farm employment may have forced households to cut down irrigation.

Table 3. Dependent variables: Log of irrigation application rates (m^3/ha).

Independent Variables	Wheat		Maize	
	M1	M2	M1	M2
Log of irrigation water price (yuan/m^3)	−0.5843 *** (5.53)		−0.4751 ** (7.35)	
Surface water × Log of irrigation water price (yuan/m^3)		−0.5002 *** (3.78)		−0.4456 (1.41)
Groundwater × Log of irrigation water price (yuan/m^3)		−0.9731 *** (4.71)		−0.4360 *** (6.76)
Conjunctive Irrigation × Log of irrigation water price (yuan/m^3)		−0.7071 *** (7.66)		−0.7222 *** (12.67)
Log of fertilizer price (yuan/kg)	−0.8374 *** (4.76)	−0.7822 *** (4.11)	−0.3841 (1.51)	−0.2820 ** (2.81)
Log of wage (yuan/day)	−0.0335 (0.05)	0.1165 (0.18)	−14.2801 *** (3.55)	−11.1582 *** (3.59)
Log of expense on machinery input (yuan/ha)	−0.0060 (0.20)	−0.0035 (0.11)	−0.3840 * (2.07)	−0.2873 * (1.88)
Log of expense on other inputs (yuan/ha)	0.4095 *** (4.00)	0.3703 *** (4.61)	1.2985 ** (2.53)	1.0039 ** (2.85)
Log of crop price (yuan/kg)	−1.1767 (0.96)	−1.9173 (1.64)	−5.6429 *** (4.41)	−4.8059 *** (3.97)
Dummy variable, =1 if water is scarce in the village	−0.0203 (0.16)	−0.0229 (0.19)	−2.6380 *** (3.25)	−1.8847 *** (3.01)
% irrigated areas in village irrigated by surface water only	0.0253 *** (5.17)	0.0279 *** (6.11)	0.0046 (1.09)	0.0049 (1.59)
% irrigated areas in village irrigated by surface water and groundwater conjunctively	0.0067 *** (3.08)	0.0067 *** (4.09)	0.0011 (0.51)	0.0038 (0.94)
Age of household head (years)	−0.0292 ** (2.42)	−0.0342 ** (2.41)	0.6748 *** (3.11)	0.4794 ** (2.81)
Years of education of household head	0.0667 (1.18)	0.0871 (1.38)	−0.8627 *** (3.63)	−0.6820 *** (4.13)
% off-farm labor in household	−0.0015 (0.83)	−0.0016 (0.85)	−0.0236 *** (5.30)	−0.0188 *** (4.11)
Log of value of house (yuan)	−0.0670 (1.14)	−0.1544 *** (2.85)	0.1557 ** (2.48)	0.1732 (0.84)

Table 3. *Cont.*

Independent Variables	Wheat		Maize	
	M1	M2	M1	M2
Plot size (ha)	0.5941 (0.59)	0.7024 (0.84)	1.0864 (1.08)	0.4764 (0.73)
Dummy variable, =1 if soil type is loam	−0.3586 ** (2.13)	−0.5081 *** (3.05)	1.0285 ** (2.10)	0.8072 * (1.81)
Dummy variable, =1 if soil type is clay	−0.0644 (0.47)	−0.1898 (1.29)	−0.1508 *** (3.13)	0.2182 (1.43)
Distance from water outlet to plot (m)	−0.0001 (1.66)	−0.0001 ** (2.12)	−0.0002 (1.42)	−0.0002 *** (2.98)
% distance from water outlet to plot that is lined canals	0.0008 (1.31)	0.0006 (1.01)	−0.0004 (0.66)	−0.0001 (0.18)
Dummy variable, =1 if drought occurred on the plot	0.0548 (0.41)	0.1130 (0.91)	−0.2962 * (1.74)	−0.2327 (1.26)
Mean temperature in growing season (°C)	−3.1886 (0.82)	−5.9238 (1.33)	1.6499 (0.23)	6.7513 (0.51)
Log of total precipitation in growing season (mm)	−2.1331 (0.44)	−1.5591 (0.32)	−4.1175 (1.15)	−11.1870 ** (2.47)
Year 2014 dummy	−1.4957 (1.18)	−2.4975 (1.67)	−2.8621 * (2.08)	−2.3572 (0.86)
Household fixed effects	YES	YES	YES	YES
Constant	54.6216 * (1.83)	83.2296 ** (2.27)	1821.7018 *** (3.75)	1459.7356 *** (3.78)
Adjusted R^2	0.855	0.877	0.824	0.879
Observations	196	196	122	122

Note: All monetary terms are in 2014 yuan; Absolute value of robust *t*-statistics in parentheses. * significant at 10%; ** significant at 5%; *** significant at 1%.

Estimation results clearly indicate a negative relationship between irrigation application rates and water prices. Estimated coefficients of water price are all negative. Except for the case of surface water irrigation in maize production, estimated coefficients of water price are also statistically significant at 1%. Since irrigation water demand functions are estimated using a log-log functional form where both application rates and water prices take log forms, price elasticities can be obtained directly from estimated coefficients of the log of water prices. All of the estimated coefficients are smaller than one in magnitude, which means that regardless of types of crops or sources of irrigation water, at current levels of water prices, irrigation water demand is inelastic.

Estimation results also show that the magnitudes of price elasticities also vary with types of crops. Demand for irrigation water in wheat production has a larger price elasticity than that in maize production (0.58 versus 0.48), and the difference is statistically significant (*t*-test = 15.79 ***). Results of estimated price elasticities by sources of irrigation reveal that the difference is largely driven by groundwater irrigation and conjunctive irrigation. This difference may be explained by two factors. First, maize has a higher water requirement than wheat. Although the growing season of maize experiences more precipitation than that of wheat, the level of precipitation is low and can only serve as a supplement to irrigation. In addition, maize grows in much hotter months than wheat. The higher temperature and consequent higher evapotranspiration (ET) significantly drives up the amount of irrigation water required to grow maize. This dictates that irrigation water demand for maize production will be less elastic ceteris paribus. Second, the price of water used in maize production is lower than that in wheat production. The average price of water on maize plots is about 0.15 yuan/m^3, about half of that on wheat plots (0.29 yuan/m^3). In general, surface water is cheaper during the growing season of maize due to more abundant supply. Because groundwater in ZB is recharged by runoff from mountainous area and seepage of river water [49], depth-to-groundwater is generally smaller in the growing season of maize, leading to lower cost of pumping groundwater. When prices are set at low levels, the corresponding price elasticities are likely to be low too. To test this conclusion further, we have run non-linear regressions that include quadratic terms of log of water prices. Estimation results of all models are consistent. Although the coefficients of both the linear term and the quadratic term of log of irrigation water price are negative, the coefficients of the quadratic terms are not statistically significant. So, it is possible that most water prices in the sample are at low levels at which demands are inelastic.

Results also indicate that price elasticities of irrigation water demand vary by sources of irrigation water. Irrigation water demand is more elastic when conjunctive irrigation is used than when surface water is used. The reason for the more sensitive price elasticity of conjunctive irrigation is the fungibility of irrigation source. Facing the same surface water price, farmers that have an alternative irrigation water source are able to switch to groundwater when the price of surface water rises significantly. When comparing the price elasticities between surface water and groundwater within a crop, there is no consistent regulation for both crops. Wheat, due to groundwater, is volumetric priced; while surface water's price is area-based [10], groundwater demand should be more elastic. However, the case of maize is not obvious, which may result from the higher water requirement of maize and the lower price of groundwater in maize's growing season.

4. Economic Returns of Irrigation Water

4.1. Descriptive Statistical Analysis

There are also variabilities in crop yield according to different crops or irrigation sources. As a whole, yield of maize was much higher than that of wheat (about 69%), which is the nature of crops; the story was consistent in different scenarios of irrigation source (Table 4). More interestingly, plots with irrigated surface water yielded the most, while plots with conjunctive irrigation had the lowest yield for each crop. This may be related to the nature of surface water, which contains more nutrient substances that are more beneficial to crop yields in surface water than in groundwater. Overall, crop yield shows an uptrend from low to high irrigation application for both wheat and maize in three irrigation scenarios. Yield of plots using surface water in general increased by 17% for wheat and 77% for maize, from the lowest quarter interval (for irrigation application) to the highest one. Similarly, for the plots using groundwater, the amplitudes of yield were 27% for wheat and 48% for maize. However, although the cases of the plots under conjunctive irrigation were not out of the story above as a whole, there were negative relationships between irrigation application rates and yields in the first three quartiles for both wheat and maize. This is due to wheat samples in the first quartile always having more precipitation, while maize samples in the first quartile had lower probability of suffering a disaster. So, we cannot determine the real relationship (of crop yield to irrigation source and their irrigation application rates) merely by using simple descriptive statistical analysis, due to many other factors affecting crop yield, like climate and disasters. We adopt multivariate econometric analysis as well.

Table 4. Crop yields (kg/ha) by quartiles of irrigation application rates in ZB.

Irrigation Application Rates Quartiles	Full Sample		Surface Water		Groundwater		Conjunctive Irrigation	
	Mean Application Rate (m^3/ha)	Yield	Mean Application Rate (m^3/ha)	Yield	Mean Application Rate (m^3/ha)	Yield	Mean Application Rate (m^3/ha)	Yield
Wheat								
1–25%	2020	5516	1863	5545	2064	4962	2841	6500
25–50%	3940	5904	3753	5900	3892	5740	5992	5563
50–75%	5866	6117	5636	6343	5142	6080	7921	5143
75–100%	9394	6285	9432	6502	8047	6308	11,344	5750
Average	5305	5955	5163	6086	4793	5778	7060	5715
Maize								
1–25%	4611	8533	4359	8181	4739	9063	4939	8475
25–50%	7253	9829	6664	9808	7094	10,500	8051	7653
50–75%	10,628	9472	9994	10,768	10,691	9214	11,045	8693
75–100%	14,605	12,488	15,100	14,019	13,485	13,000	14,363	11,557
Average	9269	10,073	9047	10,695	8994	10,399	9708	9109

Source: Authors' survey.

4.2. Estimation of Crop Production Fuction

The first step in obtaining estimates of the value of water is to estimate crop production functions. Generally, two different production functions, Cobb-Douglas (C-D) and translog, are employed in the empirical studies [61,62]. The logarithmic form of the both production functions are as follows:

$$\ln Y_{ijkt} = \boldsymbol{\eta}_{jk,3} + \gamma_1 \ln W_{ijkt} + \ln \mathbf{O}_{ijkt}\Gamma_3 + \mathbf{X'}_{ijkt}\boldsymbol{\Pi}_3 + \omega_{ijkt,3} \quad (5)$$

$$\ln Y_{ijkt} = \boldsymbol{\eta}_{jk,4} + \gamma_s \mathrm{SW}_{ijkt} \times \ln W_{ijkt} + \gamma_g \mathrm{GW}_{ijkt} \times \ln W_{ijkt} + \gamma_c \mathrm{Conj}_{\mathrm{ijkt}} \times \ln W_{ijkt} + \ln \mathbf{O}_{ijkt}\Gamma_4 + \mathbf{X'}_{ijkt}\boldsymbol{\Pi}_4 + \omega_{ijkt,4} \quad (6)$$

$$\ln Y_{ijkt} = \boldsymbol{\eta}_{jk,5} + \gamma_1 \ln W_{ijkt} + \ln \mathbf{O}_{ijkt}\Gamma_5 + (\ln \mathbf{I}_{ijkt,u} \times \ln \mathbf{I}_{ijkt,v})'\Pi_5 + 0.5^*(\ln \mathbf{I}_{ijkt,u})^{2'}\boldsymbol{\phi}_5 + \mathbf{X'}_{ijkt}\boldsymbol{\Pi}_5 + \omega_{ijkt,5} \quad (7)$$

$$\ln Y_{ijkt} = \boldsymbol{\eta}_{jk,6} + \gamma_s \mathrm{SW}_{ijkt}{}^*\ln W_{ijkt} + \gamma_g \mathrm{GW}_{ijkt} \times \ln W_{ijkt} + \gamma_c \mathrm{Conj}_{\mathrm{ijkt}} \times \ln W_{ijkt} + \ln \mathbf{O}_{ijkt}\Gamma_6 + (\ln \mathbf{I}_{ijkt,u} \times \ln \mathbf{I}_{ijkt,v})'\Pi_6 + 0.5 \times (\ln \mathbf{I}_{ijkt,u})^{2'}\boldsymbol{\phi}_6 + \mathbf{X'}_{ijkt}\boldsymbol{\Pi}_6 + \omega_{ijkt,6} \quad (8)$$

where Equations (5) and (6) are C-D specification under overall (model 1) and specific (model 2) irrigation sources, respectively, while Equations (7) and (8) are translog specification of that. In all equations, Y_{ijkt} is the crop yield from the ith plot of jth household in kth village in year t. In Equation (3), irrigation application rate W_{ijkt} enters by itself. In Equation (4), it is interacted with the three dummy variables for surface water irrigation (SW), groundwater irrigation (GW), and conjunctive irrigation (Conj). The vector $\mathbf{O}_{ijkt}$ contains non-water inputs used in crop production such as fertilizer and labor. The vector $\mathbf{I}_{ijkt,u}$ is the uth input, which constitutes the interaction and squared terms in the translog specification. A subset of the variables in $\mathbf{X}_{ijkt}$ from Equations (5)–(8) are included in $\mathbf{X'}_{ijkt}$ to control for weather conditions (temperature, precipitation, and drought). The Technology progress is represented by year.

As the result of the flexibility, translog form is a commonly used specification in the literature, which include squared and interaction terms of inputs besides the C-D terms. In other words, the C-D specification is nested in the translog specification. Thus, a testing procedure (F test) was conducted to examine whether the coefficients of the squared and interaction terms in the full model (translog) are all zero. According to F test, only the results of model 1 of maize for both fixed and random effects are statistically significant, which indicates translog form is suitable (Table 5). So, both Equations (5) and (6) are estimated for wheat, while Equations (7) and (6) are employed for maize under overall and specific irrigation sources, respectively. Moreover, Hausman test is conducted for each model. Test results indicate that household fixed effects should be used to estimate all models, except for model 2 of maize. Since fixed effects estimation will produce consistent estimates anyway, it is also used for model 2 so that the same estimation method is used for all models.

Table 5. Tests to determine crop production function specifications and estimation methods.

Tests	Wheat		Maize	
	M1	**M2**	**M1**	**M2**
F test (H_0: Coefficients on squared and interaction terms are jointly zero)				
Fixed effects (FE)	0.03	0.01	3.56 *	0.27
Random effects (RE)	0.22	0.10	5.45 **	0.01
Hausman test (H_0: difference in coefficients between FE and RE is not systematic)				
	13.64 **	26.22 ***	43.29 ***	6.76
Choices based on test results				
Functional form	C-D	C-D	Translog	C-D
Estimation method	FE	FE	FE	FE

Note: C-D stands for Cobb-Douglas production function. Translog stands for translog production function. * denotes p-value is between 5% and 10%; ** denotes p-value is between 1% and 5%; *** denotes p-value is less than 1%.

The estimation of crop production function performs well (Table 6). The goodness of fit measures (adjusted R^2) are above 0.4, which are suitable for the range of R^2s observed in other studies that use plot level repeated cross sectional or longitudinal survey data to estimate crop production functions. Notably, water is the only input that has a statistically significant coefficient in wheat production. The insignificance of other coefficients may be due to two factors. On one hand, the variations of other variables of inputs are relatively small in Zhangye, which results from the traditional cultivation of local farmers; on the other hand, irrigation plays such an important role in oasis farming that determines the survival of agriculture, which makes other inputs' functions in production not obvious. In contrast, none of the coefficients of variables of irrigation application rate in maize production are statistically significant (specifically, the calculated yield elasticity of water in the Translog function form is 0.0823 (p-value = 0.72), which is calculated based on the estimated coefficients that include water input). The reason why the coefficients of water input in maize production functions are insignificant may be correlated with the law of diminishing marginal returns of inputs, considering maize' irrigation application rates from various irrigation sources are relatively high (Table 4). The estimated coefficients of the dummy variable that indicates a plot experienced drought are negative in all regressions. This indicates that rural households have fewer means to mitigate the negative effects of drought in the growing season of crops. Probably, this is because less irrigation is available during this time period.

Table 6. Dependent variables: log of crop yield (kg/ha).

Independent Bariables	Wheat		Maize	
	M1	M2	M1	M2
Log of irrigation application rate (m^3/ha)	0.1418 *** (3.13)		4.8554 (1.61)	
Surface water × Log of irrigation application rate (m^3/ha)		0.1257 *** (3.26)		−0.1059 (0.78)
Groundwater × Log of irrigation application rate (m^3/ha)		0.1260 *** (3.04)		−0.0841 (0.59)
Conjunctive irrigation × Log of irrigation application rate (m^3/ha)		0.1605 *** (3.62)		−0.1133 (0.84)
Log of fertilizer application rate (kg/ha)	0.0388 (0.60)	0.0113 (0.17)	−2.2820 (0.80)	0.3018 (1.63)
Log of labor input (days/ha)	0.0081 (0.37)	0.0052 (0.22)	6.0417 *** (3.24)	0.0554 (0.32)
Log of expense on machinery input (yuan/ha)	−0.0112 (0.87)	−0.0112 (0.91)	−2.7000 * (1.82)	−0.0113 (0.26)
Log of expense on other inputs (yuan/ha)	0.0000 (0.00)	0.0020 (0.04)	11.1924 *** (6.71)	−0.0117 (0.05)
Interaction term of log of irrigation application rate and log of fertilizer application rate			1.1596 *** (3.26)	
Interaction term of log of irrigation application rate and log of labor input			−1.0854 *** (6.77)	
Interaction term of log of irrigation application rate and log of expense on machinery input			0.0335 (0.20)	
Interaction term of log of irrigation application rate and log of expense on other inputs			−0.1769 (0.57)	
Interaction term of fertilizer application rate and log of labor input			0.1717 * (1.73)	
Interaction term of fertilizer application rate and log of expense on machinery input			0.0334 (0.34)	
Interaction term of fertilizer application rate and log of expense on other inputs			−1.1337 *** (5.34)	
Interaction term of labor input and log of expense on machinery input			0.1906 (1.38)	
Interaction term of labor input and log of expense on other inputs			−0.2499 (0.78)	
Interaction term of expense on machinery input and log of expense on other inputs			0.2610 *** (2.87)	
Quadratic term of log of irrigation application rate			−0.7090 * (1.81)	

Table 6. *Cont.*

Independent Bariables	Wheat		Maize	
	M1	M2	M1	M2
Quadratic term of log of fertilizer application rate			0.1266 (0.44)	
Quadratic term of log of labor input			0.7861 ** (2.72)	
Quadratic term of log of expense on machinery input			−0.1373 *** (7.15)	
Quadratic term of log of expense on other inputs			−0.3578 (0.96)	
Mean temperature in growing season (°C)	0.8535 (0.70)	0.7970 (0.62)	−5.9055 (1.25)	−7.3438 (0.79)
Log of total precipitation in growing season (mm)	−0.6999 (1.06)	−0.2540 (0.41)	6.0369 *** (3.17)	−0.8057 (0.18)
Dummy variable, =1 if drought occurred on the plot	−0.1451 ** (2.50)	−0.1396 ** (2.30)	−0.2759 ** (2.60)	−0.1930 (1.32)
Technology progress (year)	0.0656 (0.74)	0.0699 (0.74)	0.0239 (0.30)	0.1023 (0.51)
Household fixed effects	YES	YES	YES	YES
Constant	−130.1452 (0.68)	−140.4255 (0.69)	46.4794 (0.21)	330.7763 (0.63)
Adjusted R^2	0.415	0.501	0.853	0.409
Observations	196	196	122	122

Note: Absolute value of robust *t*-statistics are reported in parentheses. * significant at 10%; ** significant at 5%; *** significant at 1%.

Since the production functions are estimated using log-log forms, the estimated coefficients of irrigation application rates and their interaction terms directly provide the elasticities of yields with respect to irrigation application rates. The output elasticities of wheat yield with respect to irrigation water are not statistically different when surface water or groundwater is used. According to the law of diminishing marginal production, with the increase of irrigation application rates, the marginal product of a crop will decrease. As groundwater's irrigation application rate for wheat is lower than surface water (Table 4), it has a positive effect by enlarging its marginal product, while the fact that groundwater yields less reduces its marginal product. As a result, there is no obvious distinction between the output elasticities of surface water and groundwater. The output elasticity on plots with conjunctive irrigation is higher. This is because plots with conjunctive irrigation enable farmers to irrigate crops in the moment when crops are in need of water, without the limitation of water supply. So, the marginal product of conjunctive irrigation is always high and thus its output elasticity is also big.

4.3. Economic Returns of Irrigation Water

In most parts of the world, water is not a commodity traded in the market. So, the value of water cannot be directly assessed via market price. Young [63] has the most comprehensive summary of the various methods for valuing water as an input in agricultural production. In this study, the economic value of water is imputed as the value of marginal product (VMP) of irrigation water in crop production, which is known as economic returns to water [32,35]. Jaghdani et al. [64] have shown that willingness to pay estimated using contingent valuation method is different from that generated using VMPs or residual imputation methods. Here, the VMP of water reflects the shadow price of water, while contingent valuation method is used to solicit directly stated preferences for changes to the provision of irrigation water in terms of maximum marginal willingness to pay, which is realized by related choice modelling techniques. We think VMP is the appropriate measure to be used in the analysis of water pricing policy for several reasons, since it reflects how much value a unit of water adds to crop revenue. This is different from scarcity value, in which an intertemporal framework is used to capture the value of a unit of water conserved for future periods. However, scarcity value may not represent the value of water to rural households. First, in the case of surface water irrigation, rural households receive the water allocated to them. Usually there is no storage facility to store the water for future use. Second, in the case of groundwater, there is usually a large number of households sharing the same aquifer in the village. Huang et al. [65] have shown that the common property nature of groundwater does not provide households incentive to conserve groundwater for future use. The VMP of water on the ith plot of jth household in kth village in year t is defined as:

$$\mathrm{VMP}_{ijkt} = p_{jkt} \times [\partial Y_{ijkt} / \partial W_{ijkt}] \quad (9)$$

where p_{jkt} is the price of the crop under consideration that the jth household received in year t. Using the definition of output elasticity, VMP can also be expressed as:

$$\mathrm{VMP}_{ijkt} = p_{jkt} \times \varepsilon_{\mathrm{Y,W}} \times (Y_{ijkt} / W_{ijkt}) \quad (10)$$

where $\varepsilon_{\mathrm{Y,W}}$ is the output elasticity of output Y with respect to irrigation application rate W. VMPs are imputed by multiplying the output elasticities estimated in Table 7 with crop prices, crop yields, and irrigation application rates. Since the estimated output elasticities in maize production are statistically insignificant, for the rest of the empirical analysis, we only focus on wheat.

Table 7. Average value of marginal product and price of water (yuan/m^3) for wheat in ZB.

Indicators	Full Sample	Surface Water	Groundwater	Conjunctive Irrigation
VMP	0.48 (0.15)	0.51 (0.16)	0.45 (0.14)	0.41 (0.11)
Water price	0.29	0.30	0.34	0.13
t-test for H_0: VMP-Water price = 0 [a]	2.51 **	1.85 *	2.89 ***	2.98 ***
% plots with VMP > Water price	80	81	69	100

All monetary terms are in 2014 yuan. Standard errors of VMPs are in parentheses. * denotes p-value is between 5% and 10%; ** denotes p-value is between 1% and 5%; *** denotes p-value is less than 1%. [a]. The term, PY − Wc, is regressed on W, where P is crop price, Y is output, W is water use, and c is water price. In this regression, the coefficient on W is ∂(PY − Wc)/∂W, which is the difference between VMP and water price. The hypothesis is tested using the t statistic of the coefficient on water use. Two regressions are run: in the first regression, W enters by itself; in the second regression W is interacted with three dummies that represent surface water irrigation, groundwater irrigation, and conjunctive irrigation.

VMPs are reported in Table 7. VMPs imputed for the full sample and by sources of irrigation are all around 0.5 yuan/m^3. The VMPs are 0.51 and 0.45 yuan/m^3 when surface water or groundwater is used to irrigate wheat, respectively. The VMP drops slightly to 0.41 yuan/m^3 when wheat is irrigated conjunctively by surface water and groundwater, but the difference is not statistically different (t-test = 1.61). The lower VMP is likely due to the higher irrigation application rate used under conjunctive irrigation. The marginal product of an input tends to decrease when more of it is used in production.

Although the VMPs and water prices are within the same order of magnitudes, VMPs are higher than water price in the full sample and all the three scenarios of irrigation sources. Here, we have employed t-test to examine the difference between the value of marginal product and water price. We regress (PY − Wc) on water use, W, where P is crop price, Y is crop output, and cis water price, and then examine the t tests on coefficients of W in regressions. The results indicate that there are significant gaps between VMPs and water prices under various irrigation sources. Among all wheat plots, 80% have a higher VMP of water than the price of water. The VMP of water exceeds the price of water on 81% of wheat plots under surface water irrigation, 69% of wheat plots under groundwater irrigation, and all of wheat plots under conjunctive irrigation. For plots with VMP higher than water price, about 97% of them are in the village where water is scarce and the average share of irrigated areas in village irrigated by surface water and groundwater conjunctively is only 3%. In contrast, about 75% of plots with VMP lower than water price are constrained by villages' water scarcity, and the average percentage of irrigated areas in village under conjunctive irrigation reaches 22%. This indicates that water shortage is associated with a higher likelihood of VMP exceeding water price, especially for surface water that is not volumetric priced on the plot level. Form the relatively low share of plots with VMP higher than water price (69%), we also can infer that a higher share of groundwater irrigation is associated with a higher likelihood of water price approaching VMP. In other words, as the result of deficient water supply that is constrained at a fixed level, farmers will use the maximal possible amount as long as the value of marginal product of water at that level is higher than the price.

5. Conclusions

This study estimates price elasticities of irrigation water demand and imputes economic returns of water using a set of plot levels in the midstream of HRB. The economic returns of irrigation water are defined as the value of marginal product (VMP) of irrigation water in crop production. One of the most important findings is that in a larger share of our sample, the VMPs of irrigation water, exceed the prices rural households are paying for water. This is more likely to occur in areas with more groundwater irrigation. The gap between VMP and water price can be as large as 66% of current water price. The estimated VMPs provide policy makers with some guidelines of the minimum increments in water prices required to induce water savings. If the value of marginal product is above water price, farmers will use the maximal possible amount of water that is available to them. If the government wants to stimulate farmers to save water further in this situation, it should increase the water price significantly, so it at least reaches the value of a marginal product. In addition, policy makers should be aware of the two distinctive groups of water uses. Different policy instruments may be used to induce water savings from rural households whose VMPs of water are higher than water prices and from those with VMPs lower than water prices.

The results demonstrate the importance of taking into account heterogeneity in irrigation water demand. For wheat and maize, more water is applied on plots under conjunctive irrigation than those irrigated either by surface water or by groundwater. Crop yields also differ by sources of irrigation water. Both price elasticities and VMPs are estimated by crop and by sources of irrigation water. The irrigation water demand for wheat in ZB is more price elastic than that for maize. In wheat production, groundwater demand has a larger price elasticity than surface water demand. The VMP of water is also lower on plots under conjunctive irrigation than on plots irrigated by surface water or groundwater alone. Some of these differences are driven by local conditions such as the levels of ET in different months.

There are important policy implications for ZB and also other regions in China in designing water management strategies in the agricultural water pricing reform. In recent years, China has been pursuing the comprehensive reform of agricultural water price, aiming to improve irrigation efficiency and then reduce agricultural water consumption through irrigation pricing policies. As the price maker, government should know farmers' price elasticity of irrigation water demand, which can help it forecast the effects of irrigation pricing policies, based on local water price level, cropping structure, etc. As the price takers, farmers' upper limit of affordable water price is supposed to be the economic value of irrigation water. When government makes irrigation pricing policies, it ought to take the economic returns of irrigation water into account. On one hand, water price should reach or exceed its economic returns, in order to reduce their irrigation application under the more sensitive price elasticities of irrigation water demand; on the other hand, the corresponding compensation of water price should be implemented after irrigation fee collection, such as the precision subsidy mechanism of irrigation price [11,66], considering water price has exceed economic returns of water, which can alleviate farmers' burdens. In the system, a high water price can have an incentive effect on water conservation during irrigation, and the subsidy after irrigation (usually at the end of year) can make the actual irrigation cost finally payed by farmers not rise, which results in a win-win strategy with regard to irrigation price policy.

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Appendix A

Table A1. Decomposition of key variables' variation on village level for wheat and maize, respectively.

Variable	Wheat		Maize	
	Between	Within	Between	Within
Irrigation water price (yuan/m^3)	0.21	0.10	0.13	0.07
Fertilizer price (yuan/kg)	1.54	1.29	1.59	0.97
Wage (yuan/day)	17.43	0.00	31.74	8.44
Expense on machinery input (yuan/ha)	829	869	1000	1182
Expense on other inputs (yuan/ha)	1288	1349	1274	995
Crop price (yuan/kg)	0.19	0.02	0.13	0.12
Dummy variable, =1 if water is scarce in the village	0.48	0.00	0.49	0.00
% irrigated areas in village irrigated by surface water only	43.76	0.00	45.94	0.00
% irrigated areas in village irrigated by surface water and groundwater conjunctively	36.36	0.00	44.71	0.00
Age of household head (years)	8.21	6.66	8.13	7.42
Years of education of household head	1.47	2.60	1.37	1.93
% off-farm labor in household	19.00	18.94	13.08	20.19
Value of house (yuan)	68,650	97,799	60,642	70,678
Plot size (ha)	0.06	0.06	0.04	0.03
Dummy variable, =1 if soil type is loam	0.27	0.15	0.25	0.16
Dummy variable, =1 if soil type is clay	0.39	0.36	0.37	0.37
Distance from water outlet to plot (m)	1205	872	470	442
% distance from water outlet to plot that is lined canals	32.00	27.84	35.62	29.47
Dummy variable, =1 if drought occurred on the plot	0.28	0.24	0.22	0.12
Mean temperature in growing season (°C)	2.92	0.00	2.55	0.00
Total precipitation in growing season (mm)	59.40	0.00	54.67	0.00

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