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Irrigation Water Pricing Policy in China

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Abstract

As water becomes scarcer in northern China, designing policies that can induce water users to save water has become one of the most important tasks facing China's leader. Past water policies may not be a solution for the water scarcity problem in the long run. This paper looks at a new water policy: increasing water prices so as to provide water users with direct incentives to save water. Using a methodology that allows us to incorporate the resource constraints, we are able to recover the true price of water with a set of plot level data. Our results show that farmers are quite responsive if the correct price signal is used, unlike estimates of price elasticities that are based on traditional methods. Our estimation results show that water is severely under priced in our sample areas in China. As a result, water users are not likely to respond to increases in water prices. Thus as the first step to establishing an effective water pricing policy, policy makers must increase water price to the level of VMP so that water price reflects the true value of water, the correct price signal. Increases in water prices once they are set at the level of VMP, however, can lead to significant water savings. However, our analysis also shows that higher water prices also affect other aspects of the rural sector. Higher irrigation costs will lower the production of all crops, in general, and that of grain crops, in particular. Furthermore, when facing higher irrigation costs, households suffer income losses. Crop income distribution also worsens with increases in water prices.

In summary, our paper provides both good news and bad news to policy makers. On the one hand, water pricing policies obviously have great potential for curbing demand and helping policy makers address the emerging water crisis. On the other hand, dealing with the negative production and income impacts of higher irrigation cost will pose a number of challenges to policy makers. In other words, if China's leaders plan to increase water prices to address the nation's water crisis, an integrated package of policies will be needed to achieve water savings without hurting rural incomes or national food security.

Irrigation Water Pricing Policy in China

Water scarcity is one of the key problems affecting northern China, an area that covers 40 percent of the nation's cultivated area and houses almost half of the population (Crook, 2000, Lohmar, et al., 2003, Yang and Zehnder, 2001, Yang, et al., 2003). Water scarcity in northern China has arisen both because of limited water supply and increasing water demand. Water availability per capita in North China is only around 300 m^3 per capita, which is less than one seventh of the national average and far lower than the world average (Ministry of Water Resources, 2002). Past water projects have tapped almost all of the region's surface water resources (Ministry of Water Resources, 2002). At the same time the rapidly growing industrial sector and an increasingly wealthy urban population demand is beginning to compete with the agricultural sector for water (Crook, 2000, Wang, et al., 2005a). As a result, surface supplies are becoming increasingly stressed and groundwater resources are diminishing in large areas of northern China (Wang, et al., 2005). For example, between 1958 and 1998 groundwater levels in the Hai River Basin fell by up to 50 meters in some shallow aquifers and by more than 95 meters in some deep aquifers (Ministry of Water Resource, et al., 2001).

In the past, China's leaders have implemented water policies that focused on solving China's water scarcity problems, although most of the policies only targeted the supply side solution (Lohmar, et al., 2003, Wang, 2000). Officials have given high priority to increasing water supply through developing increasingly comprehensive canal networks and constructing larger reservoirs (Boxer, 2001, Ross, 1983). Between 1980 and 1997 China invested more than 171 billion yuan into water control (measured in 1990 yuan — Fan, et al., 2002).[1] In 2001 the State Council began the construction of the US$50 billion-plus South-to-North Water Transfer Project.

It is becoming increasingly clear, however, that a supply-side only approach cannot meet the increasing demand for water from all of the different sectors in the long run. Gradually China's leaders have started to recognize the need to stem demand (Boxer, 2001). For example, since the early 1990s, leaders have encouraged households to adopt water saving technology (Lohmar, et al., 2003). Unfortunately, most of their efforts to encourage the use of many more sophisticated types of water-saving technologies, such as drip and sprinkler irrigation, have failed, and in the past several years the Ministry of Water Resources has distanced itself from a

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[1] Yuan is the unit of currency used in China—one dollar equals 8.1 yuan

water policy based on water-saving technology (Zai, 2002). In more recent years water officials also have begun to promote water management reform by providing canal managers with better incentives to save more water (Wang, et al., 2005b). However, despite the potential of producing large water savings, surface water management reform has not been effectively implemented across wide regions of China (Wang, et al., 2005b). Success in groundwater areas may be even more limited.

When trying to explain why water users have been reluctant to invest in water conservation in China's rural areas, researchers invariably have speculated about the absence of economic incentives that could be provided to water users (Liao, et al., 2005, Lohmar, et al., 2003, Yang, et al., 2003). The cost of water is fairly low. There are no extraction fees charged for the agricultural use of groundwater. In essence, groundwater for agricultural use is free; the only payment made by agricultural water users is the cost of energy (electricity or diesel). Surface water also was almost free (in the sense that water users only need to pay for the cost of delivering surface water) until the early 1990s (Liao, et al., 2005, Zheng, 2002). Despite the fact that agricultural sector is the main water-using sector in China (68% in 2001, Ministry of Water Resources, 2002), the price of water that is charged for agricultural use has not been raised much. Furthermore, inside most irrigation districts, water fees are assessed on the basis of the size of a household's irrigated area. When the cost of water is low or not related to the quantities demanded, the benefit from saving water also is low. As a result, the current water pricing policy in the agricultural sector of China (as oppose to the industrial and residential sectors) has not been effective in providing water users with incentives to save water.[2]

Under these circumstances, China's water officials and scholars have begun to consider reforming the pricing of irrigation water as one of the main policy instruments for dealing with the water scarcity problem in the coming years (Feng, 1999, Wang, 1997, Wei, 2001, Yue and Wang, 2000). It is only after the price of water correctly reflects the true value of water to water users that they will have any incentive to take actions to save water. In China's context, this means either the price of water needs to be increased or the quantity of water needs to be rationed.

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[2] China's government has raised the price of water that is charged for residential use and industrial use. For example, since 1991, the price of tap water in Beijing was raised 9 times and has increased from 0.12 Yuan per cubic meter to 3.7 Yuan per cubic meter (Chen, 2005).

While there is increasing consensus that reforming water pricing is necessary, two basic issues need to be addressed before any new set of policies can be made. The first issue is the effectiveness of increasing the cost of irrigation. That is, whether increases in the price of water will lead to a significant reduction in water use. In many developed countries, the economic literature suggests that the derived demand for irrigation is relatively price inelastic (e.g., Moore, et al., 1994, e.g., Ogg and Gollehon, 1989). If water users in China are not responsive, raising the price of water will not be an effective policy to induce sizable water savings. If water users do respond to price shifts, it is important to have some idea about the nature of the responsiveness when planning price interventions since China's leaders are still worried about food security.

In addition to water saving efficacy, it is also important to understand the impact of increasing the cost of irrigation on producer welfare. In the political-economy environment that dominates policy making in rural China today, it is absolutely imperative to assess how much producers would be hurt should pricing policies be effectively implemented (Feng and Zhang, 2005). The current government is absolutely intent on reducing farmer burdens and raising incomes even if other long term problems (e.g., the unsustainable tapping of groundwater resources) are undermined (Feng and Zhang, 2005, Lohmar, et al., 2003).

Despite the fact that approaches to dealing with water scarcity are among the most critical issues on the government agenda and that good policies require that officials understand the nature of water demand, only a handful of studies have analyzed water demand in rural China (e.g., Chen, et al., 2005, Liao, et al., 2005, Yang, et al., 2003). Many of these studies are largely qualitative. To our knowledge, there is no rigorous quantitative analysis of water demand at the farm level in China. In fact, this state of economic analysis is not unique to China; outside China studies on water demand in developing countries are predominately theoretical and rarely provide quantitative results for policy recommendations (e.g., Dinar and Tsur, 1995). Howitt and Msangi (2006) is one of the very few studies that analyze water demand quantitatively. In contrast, most quantitative studies on water demand focus on developed countries which often take place in very different economic, institutional and geographical environments (Bontemps and Couture, 2002, Howitt, et al., 1980, Montginoul and Rieu, 1997, Moore, et al., 1994, Ogg and Gollehon, 1989, Schaible, 1997, Shumway, 1973).

The overall goal of this paper is to explain the nature of household water demand and analyze the effectiveness of water pricing policies in conserving water and their impacts on the welfare of water users in rural China. To meet this overall goal, we pursue three objectives. The first objective is to describe how the cost of water (or the price of water) and water use vary across space in order to describe the relationship between water use and the price of water. The second objective is to measure the water-output relationship and to measure how responsive farmers in China are in their use of water to changes in the price of water, everything else held constant. The third objective is to analyze the impact of price increases on crop production and crop income (both levels of income and its distribution). Given the concern of leaders with both food security and rural incomes, it is imperative that the effect of water pricing changes on crop production and income are both considered when seeking to create a policy that will lead to a sustainable water pricing policy.

The rest of the paper is organized as follows. In the first section, we describe the data set that forms the basis of the study. In the second section, we examine the relationship between water cost and water use in the sample area. Such a descriptive analysis is presented first in order to inform the reader the general nature of the water economy of northern China and illustrate the observed relationship between the cost of water extraction (or the price of water) and the way that rural households in China respond in their use of water. In the third section we introduce the household profit maximization framework and the method of generalized maximum entropy that we use to estimate the coefficients of the production function and the gap between the willingness to pay for water and the current cost of water, two sets of parameters that are needed to determine water demand. The estimation results are reviewed in the next section and used in the next part of the procedure to carry out simulation analyses using the estimated parameters. The results of simulations are then used to analyze the effectiveness and impacts of water pricing policies. The final section concludes.

Due to the broad nature of the goal and objectives, we must limit the scope of the study. Because agriculture is the main water using sector (68% in 2001—Ministry of Water Resources, 2002), the data set was collected in rural communities and focuses on agricultural water use. In our study, only households that use groundwater are included. In all the sample communities that used surface water for irrigation, surface water was charged for on the basis of the size of irrigated land. Since surface water was not charged volumetrically, the level of water demand is not related with the price of water. Given the disjointedness of the water use and the price of water, surface water use is not suitable in analyzing water demand. In analyzing water pricing policies, implementation costs are excluded because information is not available.

Data Description

The data used in the study come from the 2004 China Water Institutions and Management (CWIM) Survey, a survey run jointly by the Center for Chinese Agricultural Policy in Beijing and the University of California, Davis. The enumeration team collected data in 24 communities in Hebei province, a province on the eastern coast of northern China that covers most of the Hai River Basin and surrounds the nation's capital, Beijing (Liao and Huang, 2004). About 11.7 percent of the nation's grain is produced in Hebei province (Ministry of Agriculture of China, 2004). The communities were chosen randomly from three randomly selected counties, one each from a.) Xian County is located along the coastal belt (the most water scarce area of China); b.) Tang County is located along the inland belt (an area with relatively abundant water resources that are next to the hills and mountains that rise in the eastern part of Hebei province); and c.) Ci County is located in the region between the coastal and inland belts. Because the sample sites were randomly selected, they are regionally representative. In the rest of the paper a set of population weights is used to generate statistics that provide point estimates at the provincial level.

The survey was conducted by interviewing three different types of respondents in each community (or village): the community leader; well manager (typically three randomly selected well managers per community); and households (four randomly selected households).[3] We use separate questionnaires for each type of the respondents.[4] Although most of the data in the analysis come from the household questionnaire, we also use some data from the community leader and well manager questionnaires.

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[3] Usually, the well manager in a community either owns a well or is responsible for operating the well in the community.

[4] The community leader questionnaire provided general information on the community's characteristic including demography, socio economic environment and detailed information on irrigation practices. The tubewell manager questionnaire included detailed questions about the characteristics of water resource, wells and the operation of wells. The household questionnaire included sections that collected information on household characteristics (e.g., the size of the household, its land holding and other asset), farming activities, off-farm activities and other income generating activities.

Data on household production activities

Two major blocks of data are used from the household survey: data on household production activities and data on household water use. In order to collect information on production activities, we asked respondents about household production on a plot by plot basis. The first step in doing so was to generate a "census" of all of the plots by asking farmers recount the size and irrigation status (whether the plot was irrigated and how) of each plot. According to the sample, more than 70 percent of households had at least one plot that relied on groundwater for irrigation.

For each plot, the respondent also recounted the crops that were grown during the survey year—2004. The major crops in Hebei province are wheat, maize and cotton. According to statistical sources, wheat, maize and cotton were sown on more than 60 percent of Hebei province's sown area in year 2003 (National Bureau of Statistics of China, 2004). These three crops accounted for 82 percent of the total sown area of the sample households. Wheat is the major crop grown in the field during the winter season (planted during the previous fall; harvested in the spring). After the wheat is harvested, either maize or cotton (competing summer crops) is planted and harvested in the fall. About 84 percent of the plots in the sample are double cropped.

From the list of all of a household's plots, two were selected for inclusion into the intensive crop production part of the production activities block of the survey. The plots (henceforth, *intensively surveyed plots*) were selected to capture different crops that households were growing. For example, if a household cultivated three plots and two plots were allocated to wheat and maize and one was allocated to wheat and cotton, enumerators chose the wheat-cotton plot and randomly selected one of the two wheat-maize plots. Detailed information was collected on each of the two selected plots, including information on its soil type, the distance of the plot from the farmer's home and its tenure status. For each crop, the enumerator also asked the farmer a long list of detailed questions about the yield and the cost and quantity of each type of input: fertilizer, labor (by activity), machinery (use of own equipment or hired-in custom services), pesticide and plastic sheeting.

Data on Water Use

Most importantly, a series of questions were used to elicit plot specific information on water use and water price on the intensively surveyed plots. Two general steps were needed to get farmers to provide information on water use. First, to construct a measure of the volume of water applied, enumerators asked the farmer to recount for each plot and each crop the average length of irrigation time, total number of irrigations during the entire growing season and the average volume of water applied per irrigation. When recounting the volume of groundwater that farmers used in irrigation, the respondent typically knew in fairly precise terms the length of pumping time; but he/she could only approximate the volume of groundwater pumped. To construct relatively accurate measures of water use, both the community leaders and groundwater managers were asked for detailed information on the level of the depth to water in a community's wells, information on the pump sets that were being used (the type of pump, the size of pump and the actual volume of water pumped per hour) and the typical irrigation practices used by farmers by crop (e.g., total number of irrigations; the length of irrigation time; and the volume of water applied per irrigation). Combining information from all three questionnaires, we were able to generate what we believe are fairly accurate estimates of the volume of water that was used by each sample household on each plot in 2004.

In addition, a set of questions was also designed to generate information that could be used to produce a household-specific water price. Households recounted the amount of money they spent on irrigation water. In rural China in almost all places extraction fees are not collected on groundwater (Wang, et al., 2006). This was true for our sample as well. Households only have to pay for the cost of energy (electricity or diesel) to pump the water. In most places this is either delineated in hours of operation (of the pump), kilowatt hours or actually electricity used. If households buy water from a well owner in the community, in addition to the energy cost, there will often be a service fee that is charged on per hour basis. The cost of water is calculated as total payment for water divided by the volume of water use. Fixed costs, such as those associated with sinking a well or buying a pump, are not included. In the rest of paper, the cost of water is treated as the price of water and the two terms are used interchangeably.

Nature of irrigation water demand in northern China

Since the data set contains detailed information on irrigation, we are able to analyze the nature of irrigation water demand in northern China. In this section we use the descriptive analysis to examine whether there is any systematic correlation between water use and water price. The findings of this section help motivate the choice of the methodology that we use to estimate the demand for water.

Importantly, we are able to study water demand because the sample data show that there is variation in the price of water price paid by households. The main reason that this is so is because the price of groundwater is positively correlated with the level of the depth to water (Table 1, column 1 and 2). In general, households that paid more in pumping costs per unit of water are those that were pumping from wells with greater depth to water. Moreover, according to our data, the differences in the price of water paid by different households are large. For every crop, the price of water for those households facing the greatest depth to water (column 2, row 5, 10 and15) is several times higher than the price for those households facing the smallest depth to water (column 2, row 2, 7 and 12). The price of water across the sample quartiles ranges from 0.06 yuan per cubic meter to 0.56 yuan per cubic meter (column 2).[5]

Changes in water use: Adjustments at the intensive and extensive margins

With the large variation in the prices of water across space, it becomes possible to compare the volumes of water use by households that face different water prices. While many things are not held constant in this initial descriptive analysis, we can observe a strong inverse relationship between the price of water and the level of water use: households use less water when the price of water is higher (Table 1). Moreover, the descriptive data also show that as the price of water rises, households use lower volumes of water by adjusting water use in two ways. The first way in which households adjust water use is by cutting down their water use per unit of area sown to each crop. This is defined as *adjustments at the intensive margin*. For each crop, the water use per hectare steadily decreases when the price of groundwater increases (Table 1, column 1 and 3).[6] For example, wheat-producing households that face a price of 0.084 yuan per

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[5] The price of water from groundwater sources (shown in Table 1) is almost uniformly higher than the average price of surface water in northern China (where it ranges from 0.03 to 0.1 yuan per cubic meter). The effect of China's water policy that subsidizes surface water prices is reflected in these low prices. The price of groundwater also is higher than the price of water in a number of other countries. For example, in the US the price of water is 0.08 and 0.32 yuan per cubic meter (Dinar and Subramanian, 1998). In many states of India, electricity for pumping groundwater is highly subsidized and in some places is almost free (Mukherji and Shah, 2005).

[6] It should also be noted that, on average, crop water use calculated from the survey data is consistent with findings from agronomy studies in China. The estimated crop irrigation water requirement (the difference between evapotranspiration and effective precipitation) in Hebei province, conditional on the average rainfall level between 1952 and 1998, was shown to be 2,620 cubic meters per hectare for wheat, 1,340 for maize and 1,260 for cotton (Chen, et al., 1995, Liao and Huang, 2004, Lin, et al., 2000). Taking into account irrigation system efficiencies

cubic meter water applied more than 6,433 cubic meters per hectare; other wheat-producing households that pay 0.561 yuan for each cubic meter of water used only 2,154 cubic meters per hectare. There also are large (and monotonically decreasing) water use differences by the level of depth to water for the case of maize-producing households.[7]

The second way in which households adjust their water use is by switching to less water-intensive crops or not irrigating their crops. This is defined as *adjustments at the extensive margin*. In regions in which the levels of depth to water level are greater, households tend to allocate greater shares of sown area to non-grain crops (Table 2). For example, in our data, when the sample households are ranked by depth to water, on average the households in the first quartile allocate 15 percent of their sown area to non-grain crops (row 1). The share is more than doubled for households in the third and fourth quartiles (rows 3 and 4).

In fact, such patterns are not unique to China as our findings are consistent with those of other studies on the US (Anderson, 1983, Hedges, 1977, Watson, et al., 1980). In particular, non-grain crops include vegetables, fruits, flowers and peanuts. Relative to grain crops, such as wheat and maize, many non-grain crops have a.) higher non-water costs (they are more labor- and capital-intensive); and b.) higher per-hectare net return. With increases in water prices, water has become more expensive relative to other inputs such as labor and capital and so the tendency, ceteris paribus, is to use more of other inputs. In some cases, using labor and capital more intensively could bring on a crop mix change away from grain crops toward high value crops that are more labor and capital intensive.

Constraints on water use and implications for modeling approach

The observations on the inverse relationship between water use and water price might lead analysts to the conclusion that the estimation of price elasticities of water demand (one of our main objectives) could be achieved by regressing the quantity of water use directly on the

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(which have been estimated to be between 0.6 and 0.7 in Hebei province, Chen, et al., 1995), the levels of crop water use from our data (in the column 3 of Table 1) are close to these estimates. Because the growing season of maize and cotton (late July or August to October) coincides with the rainy season in Hebei province, they require much less irrigation water than wheat.

[7] The exception is the water use of cotton producers—when comparing households in the fourth quartile (those facing the greatest depth to water) and the second and third quartiles. The levels of water use are close despite the differences in the depth to water. One possible reason is that households in the all three quartiles have reduced water use to a threshold level that the yield of cotton will be reduced greatly with lower levels of water uses. Since the level of water use is at the threshold level, it does not vary much even if the price of water is different.

price of water. Indeed our choice of communities that rely on groundwater that can be pumped without restriction was made in order to facilitate such analysis. The dual approach has been used in a number of studies that have produced estimates of elasticities of water demand in developed countries (e.g., Moore, et al., 1994).[8]

A close inspection of the data, however, casts doubt on adopting a dual approach in our sample areas. Specifically, there are two pieces of evidence in our data that indicate that the estimates of the price elasticities would be biased if we approached the estimation from the dual side. First, while there are no formal restrictions on pumping in the sample communities (Wang, et al., 2005a), our data show that in some communities there may be other ways in which the quantity of groundwater that is used for irrigation is constrained (at least short run—that is during the irrigation season). According to data from our 24 community leader survey forms, in response to a question about whether or not there was sufficient water in the wells (or accessible levels of the water) to meet demand during the irrigation seasons for 2002, 2003 and 2004, 13 leaders said there was not. In other words, according to the leaders of the communities, at the prevailing price of electricity (or diesel) there were periods of time during each season when households in their communities were not able to pump groundwater for irrigation when they needed it. In some cases (7 communities), some of the wells went completely dry (or no water could be pumped at all). The percentage of wells that ran dry ranges from 20% to 100% in these communities. In all 13 communities, the level of water in some of the wells fell so low that groundwater could only be pumped at a rate below the pump's capacity. Because of this, we believe at least in these communities, groundwater should be treated analytically as a fixed, allocatable resource. In this case, the volume of the water at the time of water application is constrained; the real value of water to the household is higher than the price at which it can be pumped out of the ground.[9] It should also be noted, however, that in the case of 11 communities, leaders said that there was no water constraint.

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[8] Moore (1994) ran a linear regression to obtain price elasticities of water demand in which the level of water use is the dependent variable and the water price is the independent variable. In many other studies that estimated input demand, a cost function or a profit function was estimated as the function of input and output prices (e.g., Morrison, 1985). These two approaches are categorized as the dual approach.

[9] To show that the gap between the willingness of households to pay for water and the actual amount households paid for water (this gap is defined in the next section as the shadow value of water) is associated with the fact that communities were short of water, we regressed the shadow values of water (which are estimated simultaneously with the coefficients of the production function —see in the next section) on a number of characteristics of each community's water resources. There are two types of wells that are sunk in rural communities: deep wells (in our survey deep wells are sunk deeper than 60 meters below the ground surface) and shallow wells (that is, wells that are

The second piece of evidence is embodied in the gap between the willingness of households to pay for water and the actual amount that they paid. In our survey we designed a block to elicit an estimate of each household's willingness to pay for water in order to understand the value that household attached to groundwater.[10] While the current price of water is relatively high (as discussed above—at least relative to other countries), there is evidence that it is below the true value to agricultural households. According to our data, the willingness to pay for irrigation water (for producing wheat, measured on a per hectare basis) is much higher, on average, than the actual amount households paid for water in 2004 (Figure 1). On average the willingness to pay is nearly two times as high as the actual amount households paid, although there were significant differences across space. In fact, in the case of 20 percent of the households, the willingness to pay was nearly equal to the actual price of water.

Hence, according to our survey data, it appears that in many communities in China, despite the lack of formal regulation by the state, households may be constrained in the quantity of water that they can use for irrigation at current prices of electricity or diesel. The nature of the constrained behavior can be illustrated graphically (Figure 2). At the current level of water price (P), a household would like to pump the amount of Q_2. Due to the constraint, however, the household can only pump at the amount of Q_1. The water constraint thus causes a kink in the

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not sunk deeper than 60 meters). We observe that for the communities that have deep wells, the communities that were short of water are often those in which the depth to water in the well dropped below the reach of pump lift. For the communities that have shallow wells, the communities that were short of water are often those where there was not enough rainfall and thus not enough recharge for groundwater. Hence, we ran two sets of regressions: one set for those communities that have deep wells (a dummy variable that is set to one if the depth to water dropped below the reach of pump lift and other water resource characteristics are the explanatory variables) and another set for communities that have shallow wells (a dummy variable that is set to one if there was not enough rainfall from the viewpoint of farmers and other water resource characteristics are the explanatory variables). In doing so, we found that in communities with deep wells, in those communities in which the depth to water in the well dropped below the reach of pump lift, shadow values were higher. Likewise, in communities with shallow wells, in those communities where there was not enough rainfall, shadow values also were higher. In summary, results from both regressions show that the shadow values of water resource are higher in the communities that are short of water.

[10] Following recently devised standard enumeration techniques, and in order to elicit information that was uniform with respect to crop type, enumerators asked about the willingness to pay for water for each of the two "intensively surveyed plots." Our approach began by asking the respondent whether or not he/she would still plant wheat if the water price were 60 yuan per mu (mu is the unit of land area used in China—one hectare equals 15 mu). If the answer was "yes" (that is, if the farmer stated that he/she would continue to plant wheat even if the water price was 60 yuan per mu), enumerators raised the water price and asked the same question for a water price of 80 yuan per mu. In contrast, if the answer was "no" (that is, if 60 yuan per mu was too high), enumerators asked the same question at a lower water price, 40 yuan per mu. The question continued until the price of water was 110 yuan per mu on the high side; and 10 yuan per mu on the low side. Using the responses from the survey, we were able to construct an interval for the willingness to pay for groundwater. For example, if the answer to 60 yuan per mu was "yes" and the answer to 80 yuan per mu was no, then the lower bound and upper bound of the willingness to pay for water as an input in wheat production was between 60 yuan and 80 yuan per mu. This was then compared to the actual amount paid.

water demand curve. Since the water demand curve is a kinked curve, the estimates of the price elasticity of water demand obtained using standard dual-side approaches would be biased.[11]

Instead, it is clear that to accurately characterize water demand, it is important to estimate the gap between the VMP of water (at the current level of water use) and the actual price that is being paid for groundwater. To do this, it is necessary to account for the resource constraint in the empirical approach. These resource constraints need to be included as inequality constraints, since they are binding for some households/communities but not for others. This requirement requires us to work on the primal side since it is difficult to include inequality constraints when using a dual approach, and hence, the gap cannot be directly estimated if the dual approach is used. In other words, to obtain accurate estimates of elasticities of water demand in our sample communities, we need to use a methodological approach that can both incorporate water resource constraints and estimate the gap between the actual price of water and the VMP of water. In the next section, we describe the framework that will be used to estimate water demand.

Model and methodology

So far the findings have been largely descriptive. In the next section we estimate water demand parameters of Chinese rural households more rigorously. To do so, we first introduce a household maximization model from which household water demand is derived. We then briefly lay out the methodology to estimate water demand, which is developed and reported in greater detail in Huang et al. (2006).

Household water demand in China

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[11] There are two other reasons that the primal approach may be more appropriate than the dual approach when researchers study developing countries. First, a primal approach utilizes more information contained in the data. It is a typical situation in developing countries that the prices of variable inputs do not vary much across space. For example, the input and output prices are almost surely the same within each village in rural China (Huang, et al., 2004). In contrast, the level of input uses vary sharply across space as can be shown using our data. The variation in input uses provides valuable information that can be used in the estimation of parameters. Since the dual approach typically only uses the prices in estimation, it forgoes lots of the information in the data, which could be used to increase the efficiency of the estimates. Second, the primal approach is more suited for policy analysis. In our case, the value of irrigation water is often measured in terms of the physical outcomes of agricultural production. The resource constraints on water and other inputs require that shadow prices be added to nominal prices when taxes or subsidies are formulated. More generally, environmental policies are often formulated as constraints on input use. Economic models of agricultural and environmental policy impacts often have to formally interact with process models of the physical systems (Antle and Capalbo, 2001). Such models require the economic output in terms of primal values.

The basic framework begins with the specification of a static household profit maximization model.[12] The household is assumed to be engaged in producing three different crops (wheat, maize and cotton) using multiple inputs. We assume two of the inputs are variable inputs: capital (x_k) and fertilizer (x_f). Capital costs, which could also be called the "material costs", include expenditures on machinery, seed, plastic sheeting, herbicides and pesticides. Fertilizer can be purchased at an unlimited quantity at the market price, c_i, where i is the index for input and in the case of fertilizer is set as c_f (Qiao, et al., 2003). Given the small sizes of China's farms, we assume each household is a price-taker in the input and output markets.

In making its output and variable input decisions, each household maximizes the annual profit from all production activities conditional on three resource constraints.[13] Water (x_w), land (x_L) and family labor (x_{fl}) are assumed to be available at limited quantities and are treated as fixed allocatable inputs (that is, they are constrained resources). In addition to water (which we showed in the preceding section to be constrained in many communities), in most villages in rural China the collective allocates land to each household based largely upon the size of the household (Kung, 2002). There is no cost for land except for the plots that are rented. Only few plots are rented (about 3 percent in 1995 and 7 percent in 2000—Brandt, et al., 2004). Hence, in our analysis, we assume there is no variable cost for land and that it is fixed. Besides family labor (which is fixed by definition), labor input also can include hired labor (x_{hl}). We assume hired labor and family labor are perfect substitutes. Since (in our data and in all of China—Benjamin and Brandt, 2002) only a small percentage of labor that is used on the farm is hired, labor also can be assumed to be mostly fixed.[14]

Working with these assumptions, the basic constrained profit maximization problem is:

$$\text{(P1)} \qquad \underset{x_{ij}}{\text{Max}}\ \sum_j p_j f_j(x_{Lj}, \gamma x_{wj}, x_{lj}, x_{fj}, x_{kj}) - \sum_i c_i x_{ij}$$

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[12] Our assumption of profit maximization is supported by other studies on production behavior in China (e.g., Huang and Rozelle, 1996, Lin, 1992). In one study that estimates crop-specific production technology, Fan and Zhang (2001), the authors do not assume the profit-maximization behavior, but not because they do not believe that China's farmers are not profit-oriented. Instead, their assumption is made because they only had aggregate data at the province level and such aggregate data often do not display the standard properties implied by profit maximization behavior. Since our data were collected at the household level and have detailed information on observed input allocation (both on costs and on quantities) at the plot level, we believe that our data are likely to be consistent with the standard properties implied by profit maximization behavior.

[13] In Hebei province wheat, maize and cotton are often grown in different season. In the empirical analysis, the resource constraints are different for each season. The season is not denoted in the profit function for the sake of brevity. Each household maximizes the annual profit from both seasons.

[14] It should be noted that in our analysis, we did not include the labor and capital spent on adopting irrigation technologies such as furrow irrigation. The reason is that we think these costs are fixed costs.

Subject to

$$\sum_j x_{wj} \le B_w \qquad (\mathrm{l}_w : \text{water})$$

$$\sum_j x_{Lj} \le B_L \qquad (\mathrm{l}_L : \text{land})$$

$$x_{lj} \le x_{flj} + x_{hlj}\,, \quad \sum_j x_{flj} \le B_{fl} \qquad (\mathrm{l}_l : \text{labor})$$

$$x_{ij} \ge 0,$$

where the output price for crop *j* is p_j and the production function for crop *j* is $f_j(x_{ij})$. Importantly, in our problem *B* represents the vector of available quantities of the fixed resources and the •$_i$s are the shadow values associated with the resource constraints.

It should be noted that water should be measured with caution as an input in crop production. Kim and Schaible (2000) and Scheierling et al. (2004) have shown that if the amount of irrigation water applied, instead of the amount of water actually consumed by the crop, is considered as the amount of water that contributes to crop growth in crop production, the marginal benefit of water, which is measured as the marginal increase in output value, can be overestimated. In other words, if the amount of irrigation water applied, instead of the amount of irrigation water consumed, is entered in the production function, $f(\cdot)$, the estimated relationship between water and output could be biased. This is due to the fact that not all the water that is applied to a plot is consumed by the crop. To account for the water that was lost during the irrigation process either due to conveyance loss or return flow to the aquifer, the amount of water actually consumed can be denoted as a proportion, •, of the amount of water applied. Therefore, although households pay for all the irrigation water they apply to their crops, only a • proportion of that water is consumed by crop. In contrast to the case of conveyance loss, another important source of water supply to crops is rainwater. To account for this effect, when we account for the total amount of water used in crop production, rain water is included together with irrigation water. Rain water is entered in crop production as a free input but is constrained to be below the level of effective rainfall.[15]

The first order condition that determines the level of household water use is:[16]

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[15] We obtained information on the level of rainfall in 2004 in the three counties in our sample. We then calculated the level of effective rainfall for each county using a formula that is used in Brouwer and Heibloem (1986) and added this to water use.

[16] Since the input uses on most plots are positive in the data, an interior solution is assumed here. Hence the dual values of non-negativity constraints are not included in the first order condition.

$$p_j \frac{\partial f_j(g)}{\partial x_{wj}} = c_w + l_w \qquad (1)$$

Equation (1) shows that household water demand is determined by farmers who are trying to balance the marginal benefits and costs of water. It should be noted that the marginal cost and marginal benefit are measured on the basis of irrigation water that is applied. This can be seen in equation (1): on the left hand side, we take the derivative of $f(\cdot)$ with respect to irrigation water that is applied, x_{wj}, not irrigation water that is consumed, $\bullet x_{wj}$; on the right hand side, c_w is the cost of irrigation water that is applied. The marginal benefit is reflected by the value marginal product (VMP) of irrigation water that is applied, $p_j \frac{\partial f_j(g)}{\partial x_{wj}}$, which is in turn determined by the relationship between water and production (that is, the production function coefficients). The VMP of water measures the household's willingness to pay for water in terms of per unit water use. The marginal cost includes *both* the actual cost a household paid for water, c_w, and the shadow value of water, $\bullet_w$.[17] In this study, in contrast to the way it is used in many other works, the shadow value is defined as the gap between the willingness of households to pay for water and the actual amount they paid for water we observed in the descriptive analysis, measured in terms of per unit of water. The shadow values cannot be directly observed and needs to be estimated.

From equation (1), it can be seen that in order to determine household water demand (which is our focus), two sets of parameters need to be estimated: the marginal product of water (which is derived from the estimates of the production function coefficients) and the shadow value of water. In our estimation procedure (Huang, et al., 2006), our empirical strategy estimates the coefficients of the production function and the shadow values simultaneously. As described below, the parameters are estimated as a single system and the estimates are generated in a way that is consistent with a.) the observed relationship between inputs and output; and with b.) a set of optimization conditions (e.g., the first order conditions and other profit maximization assumptions).

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[17] Usually when a dynamic framework is used, the marginal cost of water includes the user cost, which is measured as the forgone savings in pumping costs that will occur in future periods (Burt, 1964, Negri, 1989). The user cost arises because the pumping of one user imposes an externality on other users by lowering the level of water in the aquifer that underlies the land of other users. Since our study covers only a one-year period, the user cost of water is not included.

In summary, using our approach, we can obtain consistent estimates of price elasticities of water demand in China's rural villages. Using the framework outlined by problem P1, it is convenient to incorporate water resource constraints and other resource constraints. With the inclusion of resource constraints, problem P1 becomes a constrained maximization problem, which is consistent with the empirical evident on the nature of water resources in rural villages. More importantly, using the first order conditions derived from problem P1, we can directly estimate the gap between the actual price of water and the VMP of water (that is, which is the shadow value associated with the water constraints). With the estimates of the shadow values of water, we are able to recover the true price of water to agricultural households, which would be difficult to achieve had we used a traditional dual-side approach.

Estimating the production function and the shadow values using GME

Since the price responsiveness of water demand depends on the own- and cross-price elasticities of input demand, a flexible functional form should be used so that these relationships are not arbitrarily restricted by the choice of the functional form. In our analysis, a quadratic function is used:

$$f_j(g) = \sum_i a_{ij} x_{ij} - \sum_i \sum_{i'} x_{ij} z_{ii'j} x_{i'j} \qquad (2)$$

where $\bullet_{ij}$ is the linear coefficient on the *i*th input and $z_{ii'j}$ is the quadratic coefficient that captures the relationship between the *i*th and *i'*th input. The subscript *j* is omitted in the rest of the text since the production function is estimated on a crop-by-crop basis. In our analysis, we assume households in the same county use the same production technology.[18]

After choosing the functional form, the next step in estimating the demand for water is to specify three sets of constraints that will aid us in: a.) making the estimated results consistent with the data (the *data-consistent constraints*); b.) making our estimates consistent with

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[18] This assumption is based on the findings of a paper that we have written on selecting the optimal spatial scale of a model that is used to estimate water demand parameters. Specifically, we use the steps developed by Huang et al. (2006) to choose among three different models: a province-level model (in which all the households in different counties or villages are assumed to use same production technologies); a county-level models (in which households in the same county are assumed to use same production technologies but households in different counties are allowed to use different production technologies); and a village-level model (in which households in different villages are allowed to use different production technologies). The results show that the county-level model has the best prediction ability, which is the criterion that we used to choose the optimal spatial scale. Hence a county-level model is used for the analysis in this paper.

economic theory (the *theoretical constraints*); and c.) implementing the General Maximum Entropy (GME) estimation (the *numeric estimation constraints*).

Data-consistent constraints

When estimating the coefficients of the production function in equation (3), the first set of constraints is imposed in order to create a consistency between the estimated results and the observed data:

$$Y_n = \left(\sum_i a_i x_{in} - \sum_i \sum_{i'} x_{in} z_{ii'} x_{i'n}\right) + e_n \tag{4}$$

The observed output and input uses are denoted by Y_n and x_{in}, respectively. In equation (4), note that a subscript *n* is added to each of the variables and parameters that are household specific. For example, the notation x_{in} denotes the level of input for household *n*. The error term, e_n, can be interpreted as a variable that captures the differences in local conditions that affects the level of output (e.g., weather).

Theoretical Constraints

Three sets of theoretical constraints are used because we are estimating the production technology which is being used by the sample households to maximize profits. The first set of theoretical constraints in the GME estimation process (henceforth, the *optimality condition constraints*) in essence makes the estimates of the relationship between water and output (or any other input and output) consistent with the profit maximization behavior of each household. This is the essential relationship that we are interested in, which is defined in equation (1):

$$s_{in} = a_i - 2\sum_{i'} x_{i'n} z_{ii'} + v_{in} \tag{6}$$

The variable on the left hand side is the price of input *i* that is normalized using the price of the output. For variable inputs (fertilizer and capital) s_{in} takes on the value of c_i/p_i. In the case of fixed allocatable inputs (land, labor and water), s_{in} takes the value of $(c_i+•_i)/p_i$. It should be noted when equation (6) is added in estimation, there are actually one more set of parameters to be estimated: the set of shadow values, $•_i$, for the fixed inputs. In this paper, we estimate the $•_i$s simultaneously with the coefficients of the production function.[19]

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[19] Although by adding equation (6) there are more parameters to be estimated, in our study, the addition of equation (6) helps improve the accuracy of the estimates. Although not reported here, we compared the out-of-sample prediction performance of the estimates obtained by estimating the parameters with and without the addition of equation (6). When we compare the results we show that the estimates generated by estimating the parameters with equation (6) have smaller out-of-sample prediction errors. In other words, the estimates of our parameters are more accurate with the addition of equation (6).

The second set of theoretical constraints ensures that the production function is concave. The *curvature constraint* requires that the quadratic matrix Z (the matrix of the quadratic coefficients, $z_{ii'}$s) is positive semidefinite. This constraint on curvature is imposed by the implementation of a Cholesky decomposition of Z (Paris and Howitt, 1998). The Cholesky decomposition is defined by $Z=LL'$, where L is also an $I \times I$ matrix. The positive semidefinite property of Z is guaranteed by constraining the diagonal elements of L to be nonnegative ($L_{ii}>0$).

We also impose symmetry on Z. We do this by requiring that there is an equality between the two elements $z_{ii'}$ and $z_{i'i}$ (or that $z_{ii'} = z_{i'i}$). This is called the *symmetry constraint*.

Defining the statistical optimization criteria

The estimates are obtained through optimizing the objective function. The definition of the objective function of GME estimation is derived from the way the coefficients are estimated in GME. Instead of directly estimating the mean and variance of the coefficient in the model as is done when using OLS, when the GME method is used, a probability distribution is estimated for each coefficient and the error term. The probability distribution for an unknown coefficient is specified by choosing several possible values as the *support* of the probability distribution and assigning an initial probability to each value. Support values also are called prior values. They often come from economic theory or estimates from previous studies. The probabilities, however, are unknown and need to be estimated in the GME method through maximizing the optimization criteria subject to the constraints. Once the probabilities of the support values of each coefficient are estimated, the mean (called the *center support value*) and variance of the coefficient can be calculated.

In order to estimate a unique set of probabilities, the objective function of the GME estimation problem is defined using a concept called entropy (Shannon, 1948). The entropy of a probability distribution is defined as $-\sum_m p_m \ln p_m$, where p_m is the probability (which is unknown and to be estimated) associated with a support value (which is prior knowledge). The standard interpretation of entropy in the literature is that it provides a measure of uncertainty in the distribution of coefficients and error terms (Golan, et al., 1996). The more uncertainty there is about a parameter, the closer the probability distribution of that parameter resembles the uniform distribution.

The maximum entropy principle, developed by Jaynes (1957), is one that chooses the distribution that gives the maximum values of the entropy conditional on the constraints. In other words, the maximum entropy estimation chooses the probability distribution that is closest to the uniform distribution as the estimated probabilities subject to the constraints. In this sense, maximum entropy estimation is conservative since the uniform distribution is the most uninformative distribution and only has minimal subjective information. In my problem the selection criterion is: choose the set of probabilities (given their support values, the data-consistent and theoretical constraints and other constraints) that maximize the joint entropy of the distributions of the coefficients and the error terms. More precisely, the objective function of the GME estimation problem is:

$$\underset{p^m_{a_i},\, p^m_{z_{ii'}},\, p^m_{l},\, p^m_{e_n},\, p^m_{v_{in}}}{\text{Max}} \; H(p^m_{a_i}, p^m_{z_{ii'}}, p^m_{e_n}, p^m_{v_{in}}) = -\sum_{n=1}^{N}\left\{ \sum_m p^m_{e_n} \ln p^m_{e_n} + \sum_i \sum_m p^m_{v_{in}} \ln p^m_{v_{in}} \right\} - \sum_i \sum_m p^m_{a_i} \ln p^m_{a_i} - \sum_i \sum_{i'} \sum_s p^m_{z_{ii'}} \ln p^m_{z_{ii'}} - \sum_i \sum_m p^m_{l_{in}} \ln p^m_{l_{in}} \tag{7}$$

Numeric estimation constraints

In GME estimation, a series of steps are followed. Each of the steps entails defining one of the three additional sets of “numeric estimation constraints.” As discussed above, the first step involves specifying a discrete probability distribution for each coefficient to be estimated as well as for the error terms. These probabilities have the additional requirement that they satisfy properties of probabilities: they are positive and the probabilities of all the support values of the same coefficient or an error term add up to 1. Henceforth, this first set of numeric estimation constraints is called the *adding up constraints*.

The next step in the GME estimation process is to reparameterize the coefficients and the error terms in terms of unknown probabilities and support values. This step is implemented by defining a set of *reparameterization constraints.* The reparameterized coefficients and error terms are defined as $a_i = \sum_m p^m_{a_i} \bar{a}^m_i$, $z_{ii'} = \sum_m p^m_{z_{ii'}} \bar{z}^m_{ii'}$, $l_i = \sum_m p^m_{l_i} \bar{l}^m_i$, $v_{in} = \sum_m p^m_{v_{in}} \bar{v}^m_{in}$ and $e_n = \sum_m p^m_{e_n} \bar{e}^m_n$, where *m* is the index of the support values, the *p*’s are the unknown probabilities to be estimated. The symbols with upper bars denote the support values.

One final set of constraints is needed to ensure that, like in the case of traditional econometric analyses, the error term in the GME estimation procedure is zero in expectation. To satisfy this property, the support values for the error terms are set to be spaced symmetrically around zero. In my analysis, this is done by first setting the centering support values for the error terms ($\bar{e}^m_n$ and $\bar{v}^m_{in}$) to be the standard deviation of Y_n and s_{in} respectively. A set of weights spaced symmetrically around zero are then used to construct the support values. In addition two *moment constraints* are added to ensure the error terms are zeros in expectation terms:

$$\begin{aligned}&\left(\sum_n \sum_m p^m_{e_n} \bar{e}^m_n\right) \Big/ N = 0\\ &\left(\sum_n \sum_m p^m_{v_{in}} \bar{v}^m_{in}\right) \Big/ N = 0\end{aligned} \tag{9}$$

Summary of estimating demand parameters with GME

In summary, in estimating coefficients of the crop-specific production, the GME estimation problem can be expressed as *problem 2* (P2):

(P2) $$\underset{p^m_{\alpha_i}, p^m_{z_{ii'}}, p^m_{\lambda}, p^m_{e_n}, p^m_{v_{in}}}{\text{Max}} \; H(p^m_{\alpha_i}, p^m_{z_{ii'}}, p^m_{e_n}, p^m_{v_{in}}) = -\sum_{n=1}^{N}\left\{ \sum_m p^m_{e_n} \ln p^m_{e_n} + \sum_i \sum_m p^m_{v_{in}} \ln p^m_{v_{in}} \right\}$$
$$-\sum_i \sum_m p^m_{\alpha_i} \ln p^m_{\alpha_i} - \sum_i \sum_{i'} \sum_s p^m_{z_{ii'}} \ln p^m_{z_{ii'}} - \sum_i \sum_m p^m_{\lambda_{in}} \ln p^m_{\lambda_{in}}$$

Subject to

Data consistent constraints: $Y_n = \left(\sum_i \alpha_i x_{in} - \sum_i \sum_{i'} x_{in} z_{ii'} x_{i'n}\right) + e_n$

Theoretical constraints

Optimality condition constraints: $s_{in} = \alpha_i - 2\sum_{i'} x_{i'n} z_{ii'} + v_{in}$

Curvature conditions: *Z=LL'* ; *L*$_{ii}$*>0*

Symmetry conditions: $z_{ii'} = z_{i'i}$

Reparameterization: $\alpha_i = \sum_m p^m_{\alpha_i} \bar{\alpha}^m_i$; $z_{ii'} = \sum_m p^m_{z_{ii'}} \bar{z}^m_{ii'}$; $\lambda_i = \sum_m p^m_{\lambda_i} \bar{\lambda}^m_i$

$v_{in} = \sum_m p^m_{v_{in}} \bar{v}^m_{in}$; $e_n = \sum_m p^m_{e_n} \bar{e}^m_n$

Adding up constraints: $\sum_m p^m_{\alpha_i} = 1$; $\sum_m p^m_{z_{ii'}} = 1$; $\sum_m p^m_{\lambda_i} = 1$

$\sum_m p^m_{e_n} = 1$; $\sum_m p^m_{v_{in}} = 1$

Moment constraints: $\left(\sum_n \sum_m p^m_{e_n} \bar{e}^m_n\right) \Big/ N = 0$

$\left(\sum_n \sum_m p^m_{v_{in}} \bar{v}^m_{in}\right) \Big/ N = 0$

Estimates of the coefficients of the production function

The GME estimation performed fairly well, producing coefficients in which many of the signs appear to be reasonable and have low standard errors (Appendix 1).[20] For example, the

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[20] Since we have estimated a separate production function for each county, we examined whether the coefficients of production functions differ significantly across counties. Following Golan et al. (Golan, et al., 2001), we use an entropy-ratio test to examine whether households in different counties are using the same production technology.

linear coefficients ($•_i$s) are all positive, which is a necessary but not sufficient condition for the property that the production is increasing in the quantities of inputs. To examine the robustness of the estimation results, we used bootstrapping to obtain the standard errors by sampling the original data with replacement. The bootstrap results show that most estimated coefficients have small standard errors (Appendix 2).

The magnitudes of the coefficients also are reasonable. The production elasticities of inputs calculated using the estimated production function coefficients are within a reasonable range.[21] For example, the production elasticity of fertilizer is 0.19 for wheat, 0.13 for maize and 0.17 for cotton (Table 3, column 4). The estimates from previous studies of China's agricultural production technologies range from 0.14 to 0.30 (e.g., Fan, 1991, Lin, 1992, Zhang and Fan, 2001). The production elasticities of labor range from 0.05 to 0.11 which are also comparable to the estimates from previous studies (e.g., Dong, 2005, Fan, 1991, Lin, 1992, Wu, et al., 2005).

Finally, the own- and cross- price elasticities of many of the inputs also fall within reasonable ranges.[22] For example, the own-price elasticities of labor is less than one (e.g., it is -0.66 for wheat—Table 3, row 3). In fact, this is about the same order of magnitude as estimates from other studies (de Brauw, et al., 2000, Huang and Rozelle, 1996). When estimating substitution and complementarity relationships among the inputs, we also find that in many cases the estimated substitution elasticities are reasonable. For example, the cross-price elasticity of labor with respect to the price of capital is 0.21 for wheat, 0.27 for maize and 0.3 for cotton (not reported in Table 3). Since the cross price elasticities are positive, this means that labor and capital are substitutes for each other, a result that is consistent with the finding that in most developing countries labor and capital are substitutes (e.g., Garcia-Penalosa and Turnovsky, 2005, Khandker and Binswanger, 1992).

In our case the null hypothesis is that households in different counties are using the same production technology. Since we have five inputs and 20 parameters for each county, the number of constraints is 40. The entropy-based tests reject the null hypothesis at the 5% (or even the 1%) significance level for all three crops: the entropy-ratio statistics are 100 for wheat, 122 for maize and 125 for cotton, all of which exceed the corresponding critical value. The $•^2$ critical value is only 73.15 for a p value of 0.005.

[21] The production elasticity is defined as the percentage change in output in response to a change in an input. In most studies, a Cobb-Douglas production function is used. The output is regressed on the inputs. Since both the dependent variable and independent variables are in logarithm form, the coefficient on each input is interpreted as the production elasticity of the input.

[22] The price elasticity of fertilizer that was calculated by other studies ranged from -0.37 to -0.867 (David and Otsuka, 1994, de Brauw, et al., 2000). Our estimate is higher than those estimates from previous studies but still is within a reasonable range. According to de Brauw et al. (2000) the liberalization of the fertilizer market has made producers more sensitive to fertilizer price changes. Hence it is not surprising that we find a more elastic demand since we used data that recorded fertilizer uses and prices in year 2004, a much later period than previous studies.

Estimates of China’s water demand parameters

The importance of using a methodology that captures the characteristics of the production environment within which producers are using water and responding to water prices is shown by generating water demand parameters using traditional regression approaches and comparing them with our estimates from GME. When we estimate the linear regression of water use on the price of water, we find that the demand for water is inelastic. In all three counties—and for all three crops, the estimates of the price elasticities from simple linear regression models are under one (Column 3, Table 4). For example, the price elasticity for wheat is -0.54 in Xian County, -0.37 in Tang county and -0.27 in Xian County. Although there are no econometrically estimated water demand parameters from other studies of China (to the best of our knowledge), the estimates that are produced by our dual-based regression approach are close to those produced by studies in other countries that also use a dual approach. For example, both Moore, Gollehon and Carey (1994) and Ogg and Gollehon (1989) find that the short run water demand in the western regions of the US are inelastic. The estimates of price elasticities of water demand range from -0.05 to -0.17. In fact, in some countries these types of results (that is, results that show water demand is inelastic) have been used to argue against the adoption of policies that are based on increasing water prices (Kelso, 1967). The main point of such an argument is that the derived demand for irrigation water is price inelastic and thus changes in prices will produce little change in water demand, but will redistribute considerable amounts of income among farmers or between farmers and those that supply water. If this is true for China, then policies that are based on increasing the price of water may not be a solution to the nation’s water scarcity problems.

However, (as argued above) in the dual-based, linear regression approach the shadow values are not considered when estimating the response of producers to changing water prices. Hence, we consider the use of traditional approaches naïve, since we have shown that many households are constrained in water resources. In fact, our estimates of the shadow values (or the $\bullet_w$s) show that there are large gaps between the actual cost households paid for water and the VMP of water. One interpretation of such large gaps is that currently water is under-priced in rural China. In all three counties, the gap between the actual cost that households paid for water (or the price of water) and the VMP of water more than doubled the actual cost of water (Figure

3). For example, the average water cost is only 0.23 yuan per cubic meter in Ci County while the average value of the estimates of $\bullet_w$ is 0.64 yuan per cubic meter. Hence the VMP of water is more than two times the current cost of water (0.87 yuan per cubic meter). These results are consistent with the findings in the descriptive analyses. Given the large shadow values, the naïve approach that ignores them may lead to bias in the estimates of prices elasticities

When we use our approach that takes into account the shadow values, the calculated elasticities changed sharply when compared to estimates produced using the naïve approach. When using GME, we calculate the price elasticities of water demand based on our estimates of the value of the VMP of water. In doing so, we find that, in contrast to the results generated using the naïve approach, the demand for water is elastic for most crops in all three counties. For example, the price elasticity of water demand is -1.35 for wheat in Xian County and -1.43 in Ci County, although it is higher in Tang County (Column 1, Table 4). When we aggregate over counties, the absolute value of estimates of price elasticities of water demand are more than 2 for all three crops. Hence using our approach, we find water demand is elastic and raising water prices has the potential to help China's leaders deal with its water problems.

A summary of the results that are produced using our approach and using the naïve approach show that the price elasticities of water would have been underestimated had we relied on the traditional dual-based regression approach, or any approach that did not account for the constrained nature of water resources. The bias arises mostly from the difficulty of incorporating resource constraints into the dual approach. As a result, the analysis using the dual-based, linear regression approach cannot recover the true price of water when water is a constrained resource. Since a change in the cost of water does not necessarily cause a change in the true price of water households face (it may only change the gap between the true price of water and the cost of water), households may not adjust their water use at all. As a result, using the dual approach, the elasticities calculated would be low. To show this, we modified our approach in problem P1 by excluding the water resource constraints. As a consequence, the shadow values are not considered when the coefficients of the production function are estimated. In the next step, when we calculate the price elasticities of water demand, the current cost of water is treated as the price of water. We found that using this modified approach, the estimates of price elasticities are all below one (Column 2, Table 4). In fact, the estimates of price elasticities are close to those obtained by running the linear regression (Column 2 versus column 3).

Effectiveness and impacts of water pricing policies in rural China

In the previous section, we estimated the coefficients of the production function of farmers in northern China and used the estimated parameters to calculate a set of price elasticities of the demand for water. Although we found that water demand is elastic, it is important to remember that the price elasticities are obtained holding the level of other input uses and the size of the irrigated area constant. Such a measure may not capture the entire spectrum of responses that farmers have when the price of water changes. As we have observed in the descriptive analyses, when the price of water increases, households may respond not only by reducing their water use for each crop that they are cultivating, they may also adjust their crop mix and cut back the acreage of land. To characterize the response of producers to changes in water prices that might facilitate a new effort by the government to curb demand, we move to use simulation analyses in this section.

Procedure of simulation analyses

To implement the simulation analyses, we use the household maximization problem P1. The model is parameterized by using the estimated production function coefficients and the observed values of input and output prices from the data. The simulation proceeds by allowing households to maximize their profits by choosing the level of water input as well as other inputs, given the input and output prices they are facing. In the simulation analysis the household determines the types of crops that it will grow as well as the quantity of variable inputs, land and labor allocated to each crop. The household also makes its water allocation input and in doing so determines the total size of land that is irrigated. In this way we are able to capture adjustments that farm households are making on both the intensive and extensive margins.

Using the simulation framework, we can evaluate the responses of farm households to different water policy regimes by following a three step procedure. First, we run a baseline model by solving Problem P1 for each household in our sample using the estimated production function coefficients and the baseline water prices as discussed in the previous paragraph. Second, we increase the base water price by a certain percentage. Alternative policy regimes are mimicked by using four different percentages: 10 percent, 25 percent, 50 percent and 100 percent.

Third, the profit maximizing level of input uses and output are generated by solving problem P1 for each household for each different set of water prices.

The results of the simulations can be used in a set of policy analyses. Since we have water use for each crop, we can calculate the total water use for each household. This change in water use, unlike the price elasticities that are calculated in the preceding section, captures the adjustments both at the intensive and at the extensive margins. By comparing the average changes in household water uses under different water prices, we can predict the extent of water savings that occur when water prices are raised to different levels. Since the simulations also predict the level of total sown area and output of different crops, we can also create predictions of the impact of water pricing policy on crop production and crop income.

Effectiveness and efficiency of water pricing policy

Since from the analysis in the previous section we know that there are two sets of water prices, the observed price of water (the actual water cost households paid) and the true price of water (the VMPs of water), we can create two sets of results, simulating two different types of water policies: a naïve policy and an informed policy. When implementing the naïve policy, we assume that policy makers are not aware that there is a gap between the current (actual) water cost and the true value of water to households. As a result, officials consider the current price of water as the starting point of their policy programs and simply increase the price of water by percentages (10, 50, 90, and 100) of these costs.

In contrast, we also simulate the situation when policy makers make informed policies. To make informed policy, officials must be aware of and act on the fact that there is a gap between the actual cost of water and its true value. As a consequence, officials have to implement a two step process. In the first step, the price of water of each household is increased from its original price to a level that is equal to its VMP; after step 1, the price of water reflects the true value of water.[23] However, it should be noted that the response of households in their water use after step 1 is zero since the true price of water households face does not change. In the second step of informed water pricing policy making, the price of water is increased by the set of predetermined percentages.

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[23] In our simulations, the first step is to increase the price of water for each household to the level of VMP. In reality, it would be difficult to do since there are so many farmers. Although in our study we do not evaluate the implementation costs of policies, this is important to consider before a policy could be implemented.

When policy makers pursue a naïve policy, the most important result is that water pricing policy is not effective in achieving the water-savings goal of leaders (Figure 4, Panel A). If the price of water is raised by 10 percent, the higher water price only leads to a 1 percent reduction in household water use on average. Even if the price of water was doubled, according to our simulations, households will only reduce water use by 14 percent. Hence, according to the naïve policy analysis, it appears as if the arc elasticity of water price is far less than unity and there is little scope for using pricing policy to curb demand and address China's water problems.

The reason that the naïve water policy is so ineffective may best be seen by comparing the results to those of the informed water policy. When the informed policy is used, the effects of the pricing policy are vastly different. Once the price of water is raised to equal the VMP of water, increasing water price has a large effect on water use (Figure 4, Panel B). For example, in step 2 of the informed policy regime, a 10 percent increase in the water price leads to an 18 percent reduction in household water use. Doubling the water cost reduces household water use by 79 percent. Hence, when an informed water policy is used, raising the price of water is more effective in terms of water savings.

Our results also indicate that an informed policy is more efficient than a naïve one. In this case, we use the amount of water use reduction per yuan of water price increase as a measure of the efficiency of a policy. When an informed policy is used, prices are increased using the VMP of water as a base. When the naïve policy is used, prices are increased using the current cost of water as a base. Since in all three counties, the level of VMP is around three times the original cost of water (Figure 3), in absolute value terms, a 10 percent increase under the informed policy is roughly equivalent to a 30 percent increase under the naïve policy. As a result, when officials use an informed policy, a 10 percent increase in the price of water leads to an 18 percent reduction in household water use. In contrast, when using a naïve policy, only about 3 percent reduction (the percentage reduction corresponding to the 25 percent increase) is achieved. Hence, when the price of water is increased by the same amount, an informed policy would lead to a much higher water use reduction than a naïve policy.

Comparisons of the results in Panel A and Panel B indicate that the key to the effectiveness of the pricing policy is the recognition of the level of VMP of water relative to the actual cost of water when designing water pricing policies. The key is to first take actions to make the price of water reflect its true value. When the true value of water, the correct price signal, is used is as the starting point for water pricing policy, raising prices is more effective and efficient. It should be noted, however, that since the VMP in our sample is initially much higher than the current price of water cost, water prices would have to be increased greatly to achieve sizable water savings. Therefore, while effective in leading to water savings, when policy makers sharply increase the price of water, there may begin to be a conflict with the goal of raising incomes in rural China. This will be discussed in the next section.

Production and income impacts of water pricing policy

Although increasing the price of water has been shown to be effective in reducing water use, when making policies, leaders must also take into account the other impacts of higher irrigation costs. In this section, we examine how increasing the price of water will affect crop production and producer welfare. In the rest of our analysis, we use the informed policy regime and assume that water price increases are being imposed after the price of water has been raised to it value marginal product.

Consistent with the findings in the descriptive analysis, when the price of water is raised, households indeed will adjust their use of water at both the intensive and extensive margins (Figure 5). When the price of water is increased by 10 percent, more than 80 percent of the reduction of water use comes from adjustments at intensive margins. For example, in the case of wheat, when the price of water increases by 10 percent, in our simulation results, households reduce their water use per hectare from 4,436 m^3 to 3,670 m^3.[24] Maize and cotton producers also cut back but by smaller margins (from 1,900 m^3 to 1,494 m^3 for maize and from 1,271 m^3 to 1,039 m^3 for cotton).

At the same time, when the price of water is raised, households adjust at extensive margins as well. According to our results, when the price is raised by 10 percent, 15 percent of the total change (or 87 percent of the extensive margin adjustment) comes from the shifting from irrigated to non-irrigated agriculture.[25] The rest of the shift at the extensive margin comes from shifting crop mix. In our case, the main shift is for farmers to move out of maize, a relative water-using crop, into cotton, a less water using crop).

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[24] Due to the in sample prediction error, the values of water use per hectare from the base simulation run is slightly different from the numbers in Table 1.

[25] Since wheat, maize and cotton accounts for 82% of total crop production in our sample, we only include these three crops in our study. In the simulations analyses, households are restricted to switching between these three crops. If more cops such as non-grain crops (e.g., vegetables and fruits) are included, households will be able to adjust more at extensive margins by switching to these crops.

Significantly, as policy markers raise the prices to higher levels (from 10 to 50 to 90 to 100 percent), the proportion of adjustments from different margins changes. As the price of water increases, increasingly more of the water savings arise from savings at the extensive margin. For example, when the water price is doubled, almost half of the total water reduction comes from adjustments at extensive margins.

The policy simulations also demonstrate that adjustments at the intensive and extensive margins affect crop production in two ways. First, lower levels of water use reduce the yields of all three crops. For example, according to our simulation results, when the cost of irrigation is doubled, on average, the yields of wheat are reduced by 20 percent, maize production by 10 percent and cotton production by 4 percent. With lower yields, the level of crop production is also lower for all crops, ceteris paribus. In particular, the production of wheat is most affected. Since the growing season of maize and cotton in Hebei province coincides with the rainy season while that of wheat does not, wheat production relies more on irrigation and falls more when the cost of irrigation rises.

In addition to the reduction in production due to adjustments in water use at the intensive margin, there also will be changes in the nation's crop output due to adjustments at the extensive margin. Since (as shown in the descriptive analysis part of the paper) the adjustments at the extensive margins shift crop production to non-grain crops in addition to cutting back the size of irrigated acreage, increasing irrigation costs reduce the acreage of grain crops (wheat and maize in our case). Both adjustments will reduce the production of grain crops further. Moreover, since households adjust more at extensive margins as the cost of irrigation rises (from 10 to 50 to 90 to 100 percent), if they opted to increase the price of water by large amounts, there will be a large impact on the nation's grain production. According to our simulation results, when the price of water is doubled, the loss of wheat output due to adjustments at the extensive margins will be 27 percent.

When accounting for both the both lower yields and smaller acreage that arise from rising water costs, the simulation results predict that water pricing policy will reduce food production in China significantly. For example, when the price of water is doubled, wheat production is reduced by 44 percent (Figure 6, Panel A). Since Hebei province produces about 12 percent of China's wheat output, if the informed water policy was implemented in only Hebei, the fall in wheat output would be equivalent to more than 5 percent reduction in China's total production of wheat.[26] To put this into perspective, China's average annual wheat production between 2000 and 2004 was 92 million tons (Ministry of Agriculture of China, 2005, National Bureau of Statistics of China, 2004). During this same period, average annual wheat imports totaled 2 million tons (Ministry of Agriculture of China, 2005). Therefore, a 5 percent reduction in the wheat crop equals about 4.6 million tons, which is much larger than the average annual level of imports. In other words, higher irrigation costs will definitely affect China's food production and international food trade.

The impacts of higher irrigation costs on crop production pose a challenge to China's policy makers. On the one hand, water scarcity is among the most urgent issues facing China and water pricing policy has been shown to have the potential to resolve the water scarcity problem. On the other hand, increasing irrigation cost, by lowering crop yields and inducing the shift of production to non-grain crop, may hurt the nation's food grain security goal of achieving 95% self-sufficiency for all major grains. Irrigation has been central for China to maintain food security and will continue to be one investment that enables China to lift its future production of food and meet its food grain security goals (Huang, et al., 1999). Hence, it is important to design complementary policies to alleviate the impacts of water pricing policies on the production of grain crops.

Effects on Rural Incomes

The impact of higher irrigation costs is not limited to crop production. As a direct result of lower crop production, according to our analysis, incomes of rural households are also predicted to be lower when the cost of irrigation is higher—especially the incomes of the poorer households.[27] When irrigation costs are increased by 10 percent, on average, the model predicts that crop income decreases from 2,510 yuan per hectare to 2,424 yuan per hectare (Figure 6, Panel B). Crop income drops further, to 1,916 yuan per hectare, when the price of water is

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[26] Of course, the predicted total effects would be larger if the informed water policy were also implemented in other provinces. Therefore, our "back of the envelope" calculations should be considered as conservative. However, we also do not consider the dynamic responses over time. In the long run, farmers may invest in sinking deeper wells and thus remove the constraints on water availability in their agricultural production. There could be a rise in the adoption of water saving technology or adoption of water-saving varieties or other techniques that could limit the impact on production.

[27] When we carry out the simulation analysis, the indirect impact of changes of the cost of groundwater on other sources of incomes are ignored. In other words, other sources of household income (crop income from rainfed plots, off-farm income, livestock income and other miscellaneous incomes) are kept constant.

doubled. It should be noted that in our analysis we do not consider general equilibrium effects. In fact, if water pricing policies were implemented over large areas of China, and millions of farmers changed their crop choice (and domestic wheat production fell sharply), the price of crops would rise. If this effect were considered, the production impact of higher irrigation costs would be lower.

Perhaps even more importantly, our simulation results show that there are effects on the distribution of income. Specifically, higher irrigation costs appear to hurt poor households more than non-poor ones. In fact, such a finding is consistent with the work of Rozelle (1996) and Khan and Riskin (2001). Since cropping income contributes heavily to the income of poor households, increases in irrigation costs (or any other costs) have been shown to have a relatively large impact on their income (Huang, et al., 2005). Consequently, raising water prices also affects the inequality level of household crop income (Figure 6, Panel C).[28] For example, doubling irrigation cost leads to a 9.8 percent increase in the Gini coefficient of household crop income (from 0.40723 to 0.4472).[29]

Hence, while water policy appears to have a lot of scope for saving water, the impact of water pricing policy on producer income poses a major challenge to China's policy makers in today's political economy environment. China has made remarkable progress in alleviating poverty in its rural areas in the past and the leaders are definitely intent to continue to alleviate poverty in rural China (Rozelle, et al., 2003). The government has set the target of lifting 23.65 million people out of poverty in the next five years (Xinhua News Agency, 2006). A complex and comprehensive set of tax reform policies has been implemented over the past 5 years to limit the rises of administrative fees and taxes, a policy that in recent years has been moving towards an eventual elimination of taxation on rural households (Brandt, et al., 2005). With such a policy

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[28] There are several different concepts of equity used in the literature. In this paper, we focus on the equity in terms of income distribution. When the gap between the current water cost and VMP of water is added to the water price, the inequality level of crop income is lower (from 0.40723 to 0.3907). Since the VMP of water reflects the value of water in terms of contribution to crop income, the VMP of water is likely to be higher to households with higher crop income although these households probably pay the same cost for water as other households do. As a result, the gap between current cost and the VMP of water is higher for these households. Adding the gap to the irrigation cost will most likely lead to higher reduction in crop income among households with higher crop income. This results in a more equally distributed crop income.

[29] One possible reason is that households that have higher crop income have more flexibility in adjusting water uses. For example, they may have more land so they have higher flexibility in changing their crop mix. They may also have more capital so they can substitute away from water. Thus when facing the same level of increment in irrigation cost, households with higher crop income incur lower proportion reduction in their crop income than households with lower crop income. As a result, the Gini coefficient is higher.

environment, there will be strong resistance against any policy that results in lower rural incomes. Almost certainly if any water policy is to be used in rural China today, there will need to be a set of complementary policies that can offset the impacts of higher irrigation costs on the level and distribution of rural income.

Although there are different ways that one might proceed, one solution is to design a program that can compensate rural households for their income losses. Since rural households shoulder the burden of conserving water, they should be compensated with at least the amount of the losses of their incomes. One solution is to develop a subsidy program in tandem with the water pricing policy that would provide households with transfers to offset the reduction to income from water pricing policies. Although there may be large implementation costs (which are ignored here), according to rough calculations, if such a program were used in all of Hebei (which includes 14.3 million farm households, cultivating 8.6 million hectares of sown area — National Bureau of Statistics of China, 2004), the cost of the program would range from 708 million yuan (if water prices were raised by 10 percent) to 4.9 billion yuan (if water prices were raised by 100 percent).

Our results also can be used to show that such a policy, while partly self-funding, would in fact, have to rely on new fiscal transfers, especially as the price of water was raised to higher levels. Suppose the price of water is raised through imposing a tax on per unit of water use. When the price of water is raised only a small amount (or when it is raised from it initial actual cost to the level of the household's VMP), most of the amount needed to fund the transfer program (administrative costs aside) can come from the program (the tax revenue collected). However, as the level of the water tax increases, the deadweight loss associated with the tax becomes larger. Our results show this clearly. If households are compensated by returning to them (in a decoupled way) the collected tax revenue, the reduction in household crop income is smaller (Figure 6, Panel B).[30] However, the tax rebate is not enough to compensate completely

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[30] If the tax rebates households receive equal the amount of taxes they paid, it may undermine their incentives to reduce water use had households known beforehand the compensation mechanism. Hence, in my analysis, the rebate is given to each household in the form of a share of the total tax revenue collected in the village. The share is the proportion of the household land holding in the total cultivated area of the village. Returning the tax revenue based upon the land size makes the amount of rebate independent of the amount of water used. Meanwhile, since the level of water use is correlated with the size of land, the amount of rebate each household receive is correlated with the amount of tax they paid.

for the loss in crop income.[31] For example, with a 25 percent increase in the irrigation cost, each household loses 200 yuan of their crop income on average while only 156 yuan is collected per household as tax (Figure 6, Panel A). There is a 44 yuan gap between the income loss and the tax revenue collected. The level of the gap increases with the level of increment in the irrigation cost. When irrigation cost is doubled, the crop income loss (594 yuan) is more than twice the level of tax revenue (238 yuan).

Conclusion

As water becomes more scarce in northern China, designing policies that can induce water users to save water has become one of the most important tasks that face China's leader. Past water policies, including the policies that increase water supplies and those that promote the adoption of water saving technologies, have not been successful. With a set of plot level data, this paper looks at a new water policy: increasing water prices so as to provide water users with direct incentives to save water.

Using a methodology that allows us to incorporate resource constraints, we are able to recover the true price of water and generate what we believe are more accurate measures of the responsiveness of households to changes in water prices. Our results show that farmers are quite responsive when the correct price signal is used, unlike estimates of price elasticities that are based on traditional methods (which do not consider the shadow value of water resources). Therefore, one explanation of why water demand policies were not used in the past is because previous estimates—which were based on incomplete methods in the case of rural China—were too low, when in fact households would be quite responsive in reducing their water use when the price of water rises.

Our estimation results show that the current cost of water does not reflect the true value of water. In fact, water is severely under priced in our sample areas in China. As a result, water users are not likely to respond to increases in water prices. Thus as the first step to establishing an effective water pricing policy, policy makers must increase water price to the level of VMP so that water price reflects the true value of water, the correct price signal. Increases in water prices once they are set at the level of VMP, however, can lead to significant water savings. In other

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[31] In the first step when the water price is increased to the level of VMP, the input uses and level of output are not affected. The reduction in crop income is exactly the increase in water cost. Hence if the tax revenue is returned to households, crop income is not changed.

words, unlike past water policies, increasing water prices, by directly giving users incentives, has the potential of resolving the water scarcity problem in China.

However, our analysis also shows that higher water prices also affect other aspects of the rural economy. Higher irrigation costs will lower the production of all crops, in general, and that of grain crops, in particular. Furthermore, when facing higher irrigation costs, households suffer income losses. Crop income distribution also worsens with increases in water prices. As a result, it is imperative that complementary policies should be used to offset these negative impacts. For example, the government can invest in developing and promoting new technologies that increase yields without using more water. A comprehensive set of subsidy policies will be needed to offset the loss in income. To be effective in reducing water, of course, subsidies must be decoupled from production decisions.

In short, our paper provides both good news and bad news to policy makers. On the one hand, water pricing policies obviously have great potential for curbing demand and helping policy makers address the emerging water crisis. On the other hand, dealing with the negative production and income impacts of higher irrigation cost will pose a number of challenges to policy makers. In other words, if China's leaders plan to increase water prices to address the nation's water crisis, an integrated package of policies will be needed to achieve water savings without hurting rural incomes or national food security.

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Table 1. The cost of water, depth to water and water use per unit of land in Hebei Province's groundwater-using communities, 2004.

	Percentile of the cost of water	(1) Depth to water (m)	(2) Average cost of water (yuan/m^3)	(3) Volume of water use per unit of land (m^3/ ha)
	Wheat			
1	Average	31	0.24	4,608
2	0-25%	14	0.08	6,433
3	26-50%	21	0.20	5,285
4	51-75%	52	0.30	2,934
5	76-100%	53	0.56	2,154
	Maize			
6	Average	34	0.24	2,019
7	0-25%	20	0.06	2,255
8	26-50%	34	0.16	2,094
9	51-75%	57	0.26	1,463
10	76-100%	68	0.52	1,119
	Cotton			
11	Average	51	0.29	1,241
12	0-25%	41	0.14	2,322
13	26-50%	46	0.23	931
14	51-75%	47	0.33	994
15	76-100%	108	0.51	978

Data source: Authors' survey in 2004 (CWIM data).

Table 2. The depth to water and crop mix in Hebei Province's groundwater-using communities, 2004.

Percentile of the depth to water	(1) Average depth to water [a] (m)	(2) Average share of household sown area that cultivates non-grain crop [a] (%)
0-25%	6	15
26-50%	21	25
51-75%	58	33
76-100%	91	31

Data source: Authors' survey in 2004 (CWIM data).

Table 3. Production elasticities and prices elasticities of inputs by crop in Hebei Province's groundwater-using communities, 2004.

	Production elasticities [a]			Own input price elasticities [b]		
	Wheat	Maize	Cotton	Wheat	Maize	Cotton
Land	0.12	0.19	0.15	-0.46	-0.45	-0.12
Water	0.42	0.17	0.14	-2.71	-2.82	-2.82
Labor	0.05	0.10	0.11	-0.66	-0.44	-1.24
Fertilizer	0.19	0.13	0.17	-2	-2.59	-0.98
Capital	0.10	0.08	0.12	-3.48	-3.72	-1.86

a. The elasticity of production with respect to the *i*th input, $\bullet_i$, is defined as follows: $\bullet_i=(\bullet Y/\bullet x_i)\cdot(x_i/Y)$, where Y is the output and x_i is the level of the *i*th input.

b. The own price elasticities of the *i*th input, $\bullet_i$, is defined as follows, $\bullet_i=(\bullet x_i/\bullet p_i)\cdot(p_i/x_i)$, where x_i is the level of the *i*th input and p_i is the price of the *i*th input. The price of input is ci for variable inputs and $c_i+\bullet_i$ for fixed inputs.

Table 4. Comparison of own price elasticities for derived water demand using different approaches in Hebei Province's groundwater-using communities, 2004.

		(1) Elasticities estimated by primal approach with water resource constraints	(2) Elasticities estimated by primal approach without water resource constraints	(3) Dual-side linear regression [a]
Xian County	Wheat	-1.35	-0.29	-0.54
	Maize	-4.17	-0.81	-0.53
	Cotton	-0.91	-0.16	---
	Aggregate	-2.28	-0.50	-0.36
Tang County	Wheat	-4.91	-0.36	-0.37
	Maize	-0.19	-0.05	-0.47
	Cotton	-5.61	-0.09	---
	Aggregate	-3.92	-0.23	-0.29
Ci County	Wheat	-1.43	-0.22	-0.27
	Maize	-2.56	-0.73	-0.25
	Cotton	-5.47	-0.65	---
	Aggregate	-1.92	-0.45	-0.31
Province	Wheat	-2.71	-0.67	-0.39
	Maize	-2.82	-0.34	-0.49
	Cotton	-2.82	-0.40	-0.23
	Aggregate	-2.74	-0.78	-0.46

a. Cotton is not included in column (3) because the number of observations (per village) of cotton is small (frequently only one or two sample households per village).

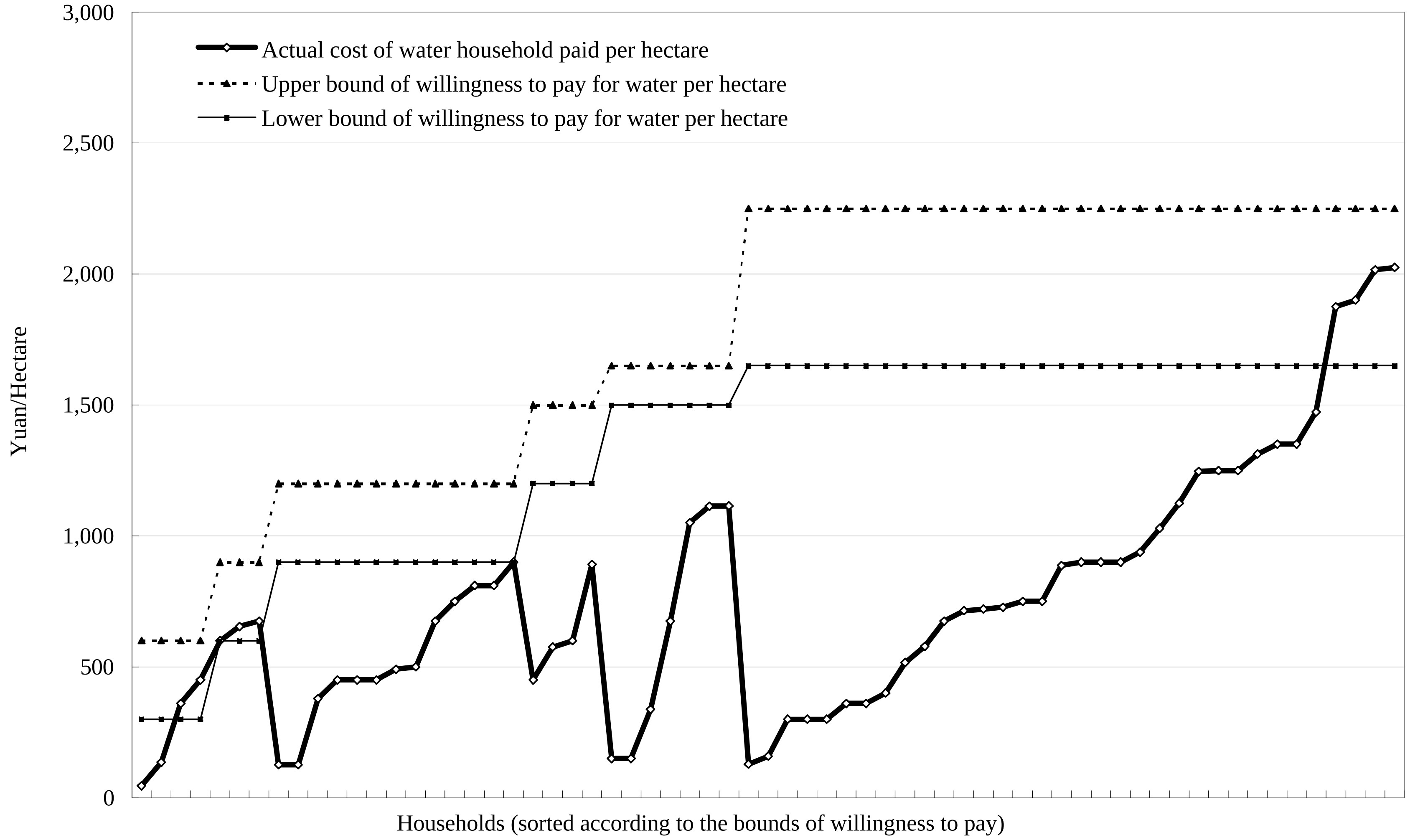


Figure 1. Actual amount households paid for water and the willingness of households to pay for water when irrigating wheat

Data source: Authors' survey in 2004 (CWIM data).

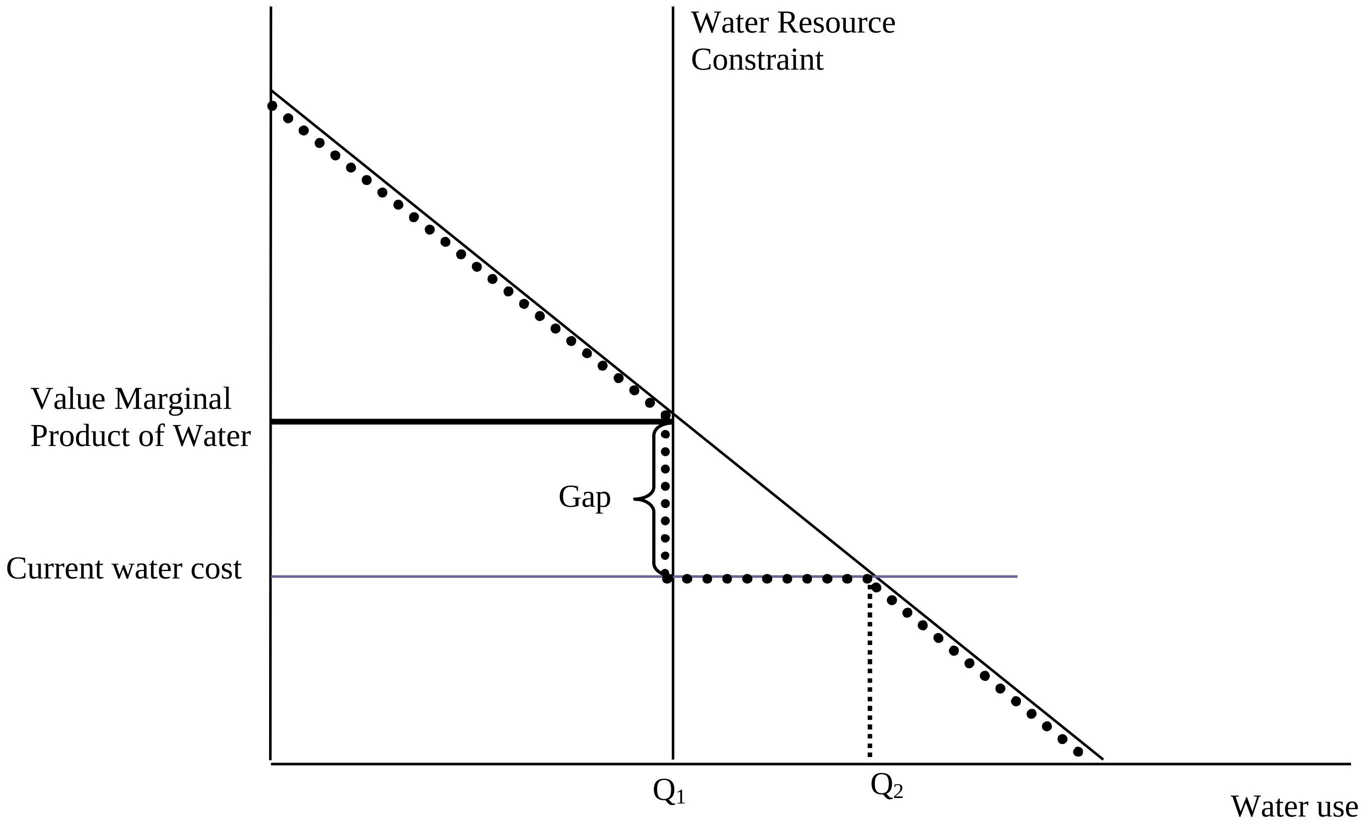


Figure 2. Illustration of the nature of water demand for households that face water resource constraints

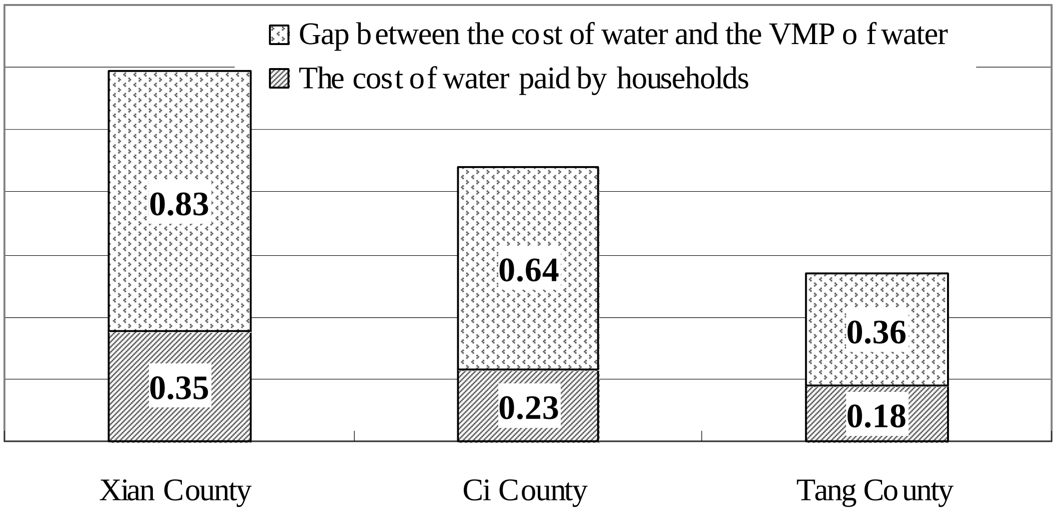
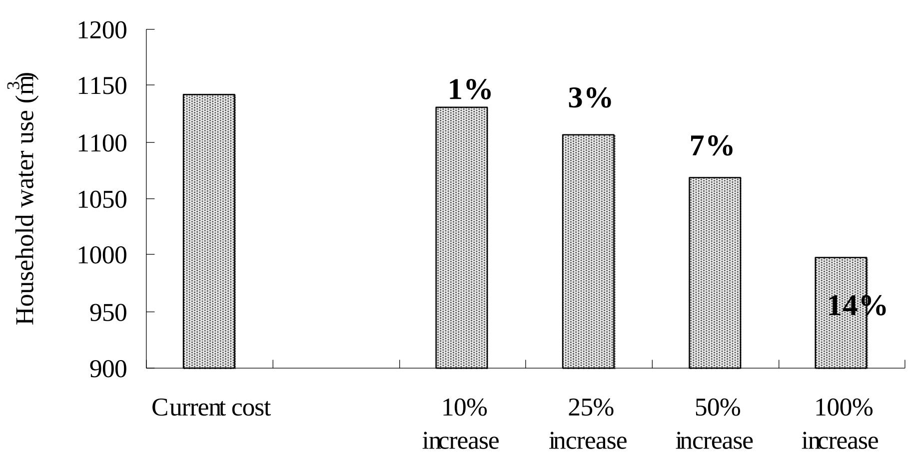
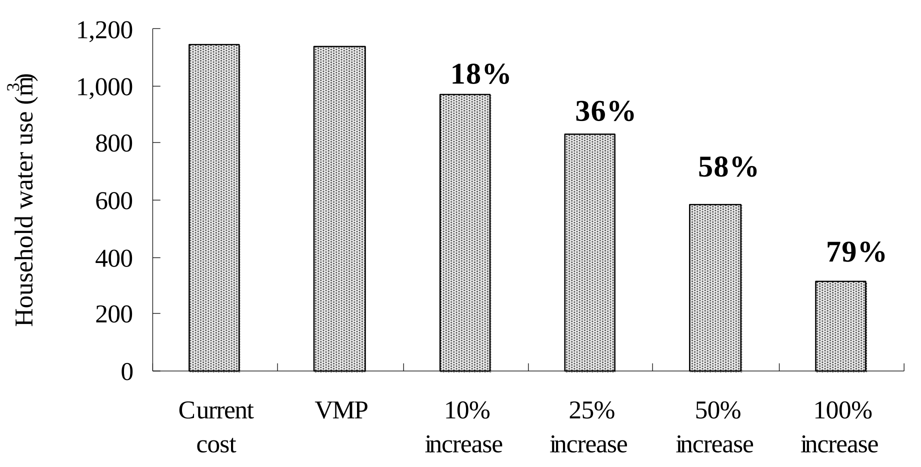


Figure 3. Comparison of the value marginal product of water and the cost of water (Yuan/m^3)



Panel A. The naïve policy: The price of water is increased in percentages of the current water cost



Panel B. The informed policy: The price of water is increased in percentages of the value marginal product of water

Figure 4. Policy analyses using simulation results: the impact of increasing the price of water on household water use

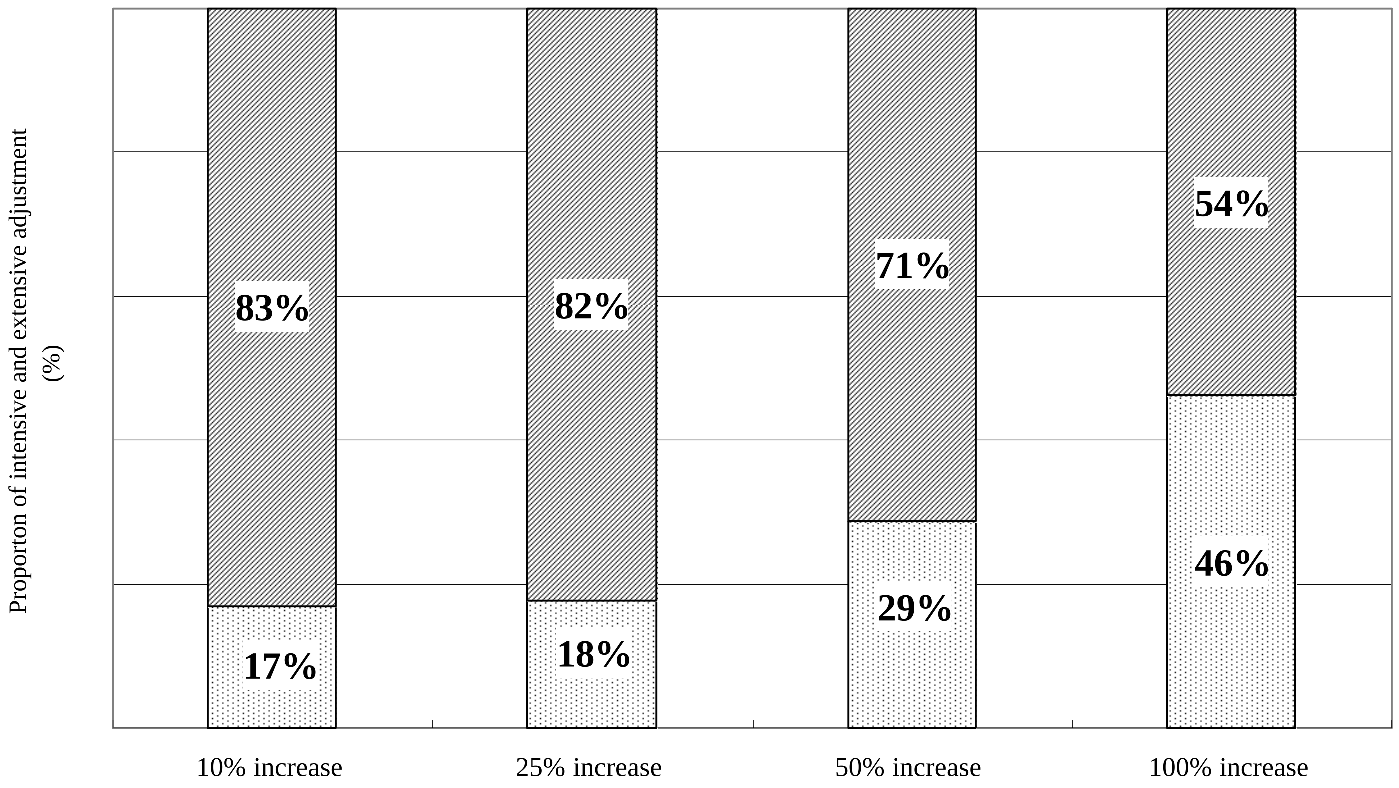
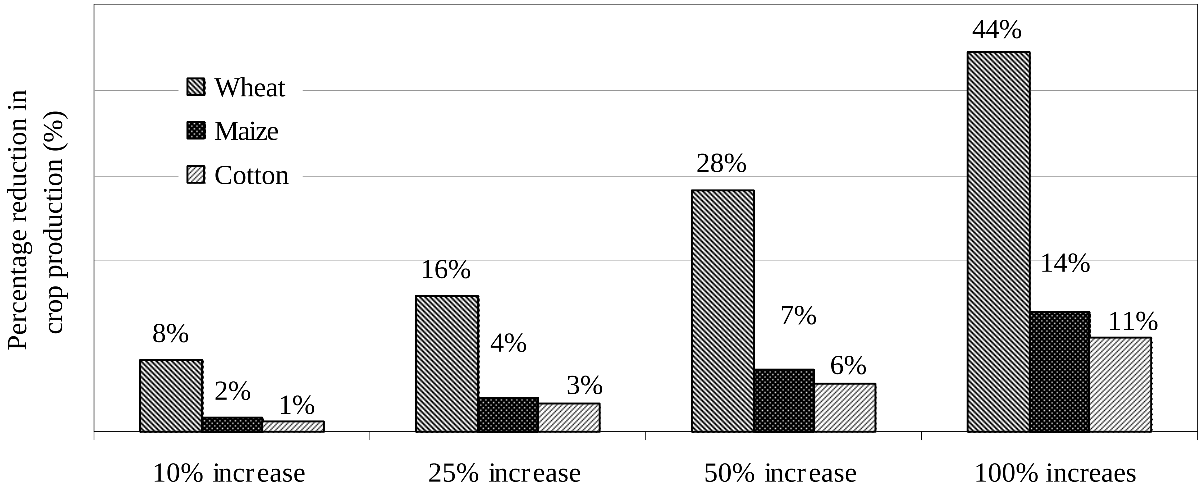


Figure 5. Policy analyses using simulation resutls: the impact of increasing the price of water on the composition of water use adjustments using the informed policy

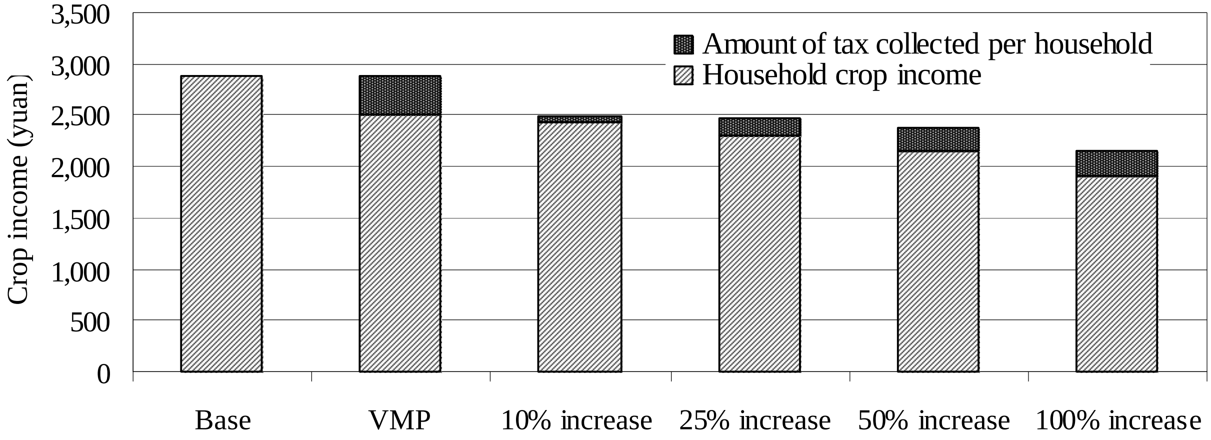
▨ Intensive margin adjustment: stress irrigation

░ Extensive margin adjustment: changes in crop mix or switch to rainfed

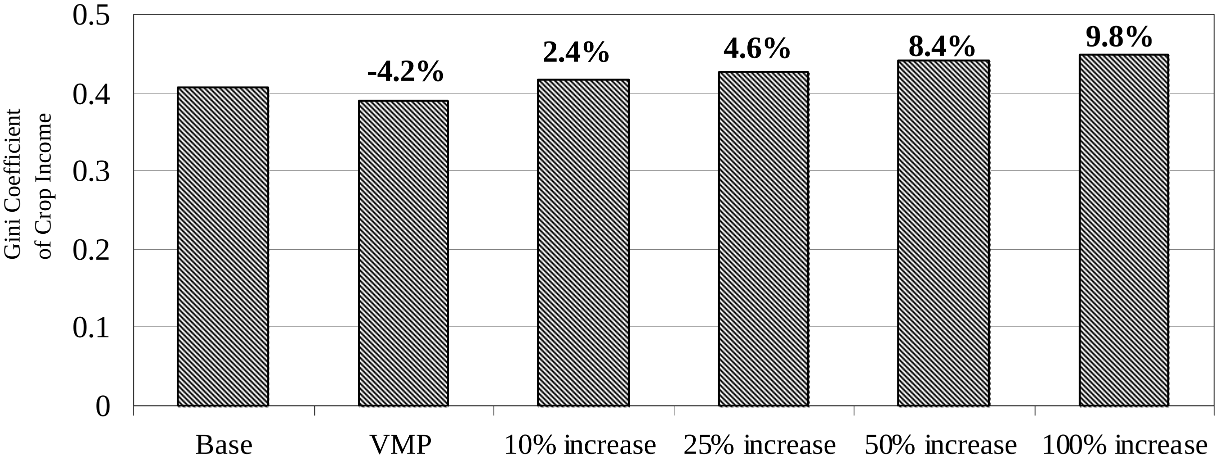
Note: The proportions of intensive margin adjustment add up to 1.



Panel A. Impact of higher water prices on crop production



Panel B. Impact of higher water prices on crop income



Panel C. Impact of higher water prices on the inequality level of crop income

Figure 6. Policy analyses using simulation results: Impacts of increasing the price of water on crop production and crop income using the informed policy

Appendix 1. GME estimates of the production function coefficients [a]

		$\bullet_i$	$Z_{ii\bullet}$ [b]				
			Land	Water	Labor	Fertilizer	Capital
Wheat Xian County	Land	0.02	0.0414				
	Water	3.84	-0.219	2.9418			
	Labor	0.91	-0.0122	-0.2671	2.5157		
	Fertilizer	1.38	-0.0738	-0.2647	-0.1085	1.1265	
	Capital	1.29	0.0041	-0.0002	0.1052	-0.1113	0.0412
Wheat Tang County	Land	0.15	0.3648				
	Water	1.24	-0.7789	2.3979			
	Labor	2.14	0.0947	-0.1353	24.2941		
	Fertilizer	0.83	-0.0981	-0.3417	-3.4585	1.8878	
	Capital	1.29	-0.0235	-0.0115	-0.3118	-0.0225	0.489
Wheat Ci County	Land	0.16	0.0684				
	Water	3.84	-0.038	5.6908			
	Labor	1.66	-0.0884	-0.1941	6.9044		
	Fertilizer	0.99	-0.0606	-1.8398	-0.1614	1.6172	
	Capital	1.33	-0.0151	-0.1118	-0.1315	0.0066	0.4461
Maize Xian County	Land	0.41	0.4001				
	Water	1.57	-1.3726	5.5686			
	Labor	1.65	0.2176	-3.0163	8.1322		
	Fertilizer	1.64	-0.4284	0.8564	-0.0963	2.1312	
	Capital	2.10	0.2886	-0.8295	-0.621	-0.9537	4.6179
Maize Tang County	Land	0.12	1.9552				
	Water	3.21	-6.4914	22.379			
	Labor	2.34	2.2608	-6.9123	8.9339		
	Fertilizer	2.34	0.5228	-1.7797	0.6525	4.112	
	Capital	2.99	1.1407	-5.8086	-1.1886	2.2503	24.8904
Maize Ci County	Land	0.49	0.6279				
	Water	1.49	-1.7985	7.4508			
	Labor	1.14	-1.0165	-0.2668	9.5767		
	Fertilizer	1.43	-0.5807	0.389	-1.0588	6.1976	
	Capital	2.20	1.1491	-4.1578	-1.4051	-3.0762	13.8347
Cotton Xian County	Land	0.32	0.0873				
	Water	0.97	-0.1118	3.1288			
	Labor	0.50	0.0464	-0.33	0.2136		
	Fertilizer	1.20	0.1021	-1.074	0.4427	2.257	
	Capital	0.90	-0.0019	0.065	0.0337	0.1752	0.504
Cotton Tang County	Land	0.19	0.0945				
	Water	0.72	-0.5474	3.814			
	Labor	0.60	0.0172	-0.1328	0.3868		
	Fertilizer	1.06	0.5404	-3.2126	0.1025	3.4341	
	Capital	0.76	0.1233	-0.7926	0.0248	0.1641	1.0837
Cotton Ci County	Land	0.13	0.1706				
	Water	1.02	-0.685	5.6359			
	Labor	0.28	-0.1048	-0.0193	0.3792		
	Fertilizer	0.84	0.6861	-2.963	-0.1815	2.9604	
	Capital	0.68	-0.2914	-0.1478	0.8526	-0.7883	3.0219

a. Land is measured in square meters; water is measured in cubic meters; labor is measured in hours; Fertilizer is measured in jin (the metric for weight in China, 1jin=0.5Kg); Capital is measured in yuan ($1 = 8.21 yuan); yield is measured in jin per square meter. Only the lower triangle of the *Z* matrix is reported since it is symmetric.

b. The values of the elements of the matrix Z are reported in the unit of 10^{-3}. Since the matrix Z is a symmetric matrix, we only list the elements in the lower triangular.

Appendix 2. Bootstrap results of GME estimation of the production function coefficients for wheat in Xian County — Linear coefficient on water, •$_w$