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Groundwater Quota versus Tiered Groundwater Pricing: two Cases of Groundwater Management in north-west China

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Abstract

Difficulties in monitoring groundwater extraction caused groundwater regulations to fail worldwide. In two counties in north-west China local water authorities have installed smart card machines to monitor and regulate farmers' groundwater use. Data from a household survey and in-depth interviews are used to evaluate the effectiveness of the different regulatory institutions implemented with help of the smart card machines. In the given context, groundwater quota is more effective in curbing farmers' groundwater use than tiered groundwater pricing. The study shows that the usefulness of smart card machines for water saving varies depending on their embedding in a certain societal context and related regulatory institutions.

Keywords: Groundwater regulation; tiered groundwater pricing; water policy reforms; smart card machines; China

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1 **1 Introduction**

2 Around the globe groundwater use for irrigation has increased ten-fold over the last half
3 a century. China is one of the countries which contributed most to this worldwide
4 development. In China groundwater was hardly used until the 1950s, while groundwater
5 extraction reached around 100 km³/year by 2000 (Wada et al., 2010). Within the country
6 most groundwater is used by the agricultural sector in the North, where around 5 million
7 tube wells are in use for irrigation purposes (J. X. Wang, Huang, Rozelle, Huang, & Zhang,
8 2009). The increased use of groundwater is seen as one of the main factors which
9 improved Chinese farmers' income from agriculture over the last decades (J. X. Wang,
10 Huang, Huang, & Rozelle, 2006). However, these benefits are threatened by unsustainable
11 groundwater use and steadily falling groundwater tables (Kendy, Zhang, Liu, Wang, &
12 Steenhuis, 2004; C. M. Liu, Yu, & Kendy, 2001; Zhen & Routray, 2002). The problem is
13 well-acknowledged in China and policies to bring groundwater overexploitation to a halt
14 have been promoted on the national level. The national Water Law, revised in 2002,
15 authorizes strict regulations on groundwater use in areas of severe groundwater overdraft
16 (Shen, 2015). However, like elsewhere in the world, it has proven very difficult to
17 implement effective groundwater regulation measures (Calow, Howarth, & Wang, 2009;
18 Shah, 2007; Shen, 2015; J. X. Wang, Huang, Rozelle, Huang, & Blanke, 2007). One of
19 the main reasons is that groundwater is an invisible resource, pumped by a high number
20 of autonomous users which makes it hard to monitor the volume of groundwater extracted
21 by each user (Hoogesteger & Wester, 2015). Another, more political reason is that local
22 authorities usually lack the motivation to implement groundwater regulations due to the
23 disparity between short-term costs and long-term benefits (De Stefano & Lopez-Gunn,
24 2012).

25 To improve the groundwater monitoring conditions the installation of water meters linked
26 to a digital administration system has recently gained popularity in China (Aarnoudse,
27 Bluemling, Wester, & Wei, 2012; C. L. Liu, Yang, & Wang, 2009). These so-called "smart
28 card machines" are connected to the pumping installation. The pump is turned on by
29 swiping a smart card at a display on the machine. The extracted water volume is measured
30 by the built-in water meter. As soon as the pumped volume surpasses the water account
31 on the card, the pump is turned off automatically. Subsequently, the card can be reloaded

at a central administration point. The installation of one smart card machine costs approximately 2500 CNY (CNY 1= EUR 0.12 in 2013). This new technology allows close monitoring of farmers' groundwater pumping at an affordable prize in the Chinese context. However, to what extent the machines support an effective regulation of groundwater use depends on the institutions behind the machine's use i.e. the rules that define who has access to the card; under what conditions the card can be reloaded etc. These rules are set by the water authorities and thus coined by these authorities' motivation for regulating groundwater pumping. Furthermore, these rules are realized in a societal context that also has a major influence on how effective the new technology is.

This article presents the case of two counties located in north-west China. Economic development in the region is less advanced than in China's coastal areas. Limited water resources are considered to pose a major challenge to new initiatives by the Chinese government to stimulate the economy in this region (Li, Qian, Howard, & Wu, 2015). In both counties smart card machines for groundwater management are installed, but operated in combination with different regulatory institutions. In the case of Guazhou County the machines are used to implement tiered groundwater pricing. Tiered pricing means that "individuals pay a low rate for an initial consumption block and a higher rate as they increase use beyond that block" (Schoengold & Zilberman, 2014, p. 2). Officially the tiered water pricing is expected to stimulate users to save water, while securing a limited amount of water at affordable levels for all users. In the case of Minqin County the machines are used to regulate farmers' groundwater use quantity through a groundwater quota system. In a quota system, total water use is controlled by allocating each user a maximum allowable quantity of water withdrawal. In Minqin, a volumetric groundwater pricing system has also been implemented after installation of the machines. However, here the groundwater fee is based on a fixed price per volume and from the outset meant for cost recovery. The two regulatory institutions implemented in Minqin and Guazhou are based on different resource allocation mechanisms. The allocation of groundwater quotas could be understood as a form of centralized planning, while groundwater pricing intends to set economic incentives and create a market mechanism. However, because the groundwater price is determined by the authorities to include a scarcity factor, both regulatory institutions highly depend on bureaucratic management.

63 *In theory*, both regulatory institutions could be effective measures to curb farmers'
64 groundwater use. Based on a modelling exercise of farmers' long-term profit under
65 different regulations, Madani and Dinar (2013) show that both quota and pricing are able
66 to curtail farmers' groundwater use. They predict that groundwater quotas are more
67 effective than groundwater pricing to render farmers' groundwater use sustainable on the
68 long run when it is assumed that farmers prioritize short-term over long-term benefits.
69 However, their model does not account for a tiered pricing system, which they expect to
70 result in better outcomes. The effect of tiered pricing systems on efficient water use has
71 been modelled by Schoengold and Zilberman (2014). They come to the conclusion that
72 tiered pricing can be effective, but the volume and water price of the initial consumption
73 block need to be set carefully, taking into consideration case specific conditions.

74 *In practice*, the pricing of agricultural water use shows mixed results and its effect highly
75 depends on local production conditions (Bjornlund, Nicol, & Klein, 2007). Based on a
76 review on practical cases of volumetric pricing for surface water irrigation, Molle (2009)
77 concludes that all over the world water quotas are a more popular regulatory institution to
78 deal with water scarcity than water pricing. The problem with water pricing is that due to
79 bulk deliveries to a group of users volumetric prices are rarely passed on to the individual
80 user. Moreover, water quotas can be adjusted more easily to seasonal variability in water
81 availability compared to water prices. He also argues that when quotas are reduced this is
82 usually done evenly for all users, incorporating principles of equity. These arguments are
83 based on the context of surface water irrigation, which means that they are not necessarily
84 valid for groundwater irrigation.

85 This article discusses the effectiveness of water quota versus tiered water pricing in a
86 setting of intensive groundwater use, based on two empirical case studies. The primary
87 focus is not on the theoretical understanding of the two regulatory institutions, but on its
88 use in a societal context. The objective of the research extends beyond the question
89 whether the regulatory institutions were effective in curbing farmers' groundwater use. It
90 also explores how the effectiveness of the regulatory institutions is related to the way they
91 are implemented and coined by the underlying motivation of local water authorities to
92 control groundwater use.

The article is structured as follows. First, the research approach is introduced by providing some background information on the study area, the data collection and data analysis. Then, two case studies are presented in separate sections. Finally, the findings are compared to draw conclusions.

2 Research Approach

2.1 Case Study Area

The two case study areas, Minqin and Guazhou (formerly Anxi) County, are both located in the Hexi Corridor, north-west China. The Hexi Corridor is a strip of flat land between the Qilian Mountains in the Southwest and sandy deserts in the Northeast. The natural corridor connected ancient China with the West and was part of the Silk Road trade route. Despite its (semi-) arid climate, the plains have long been productive agricultural areas due to abundant melt water flowing down the Qilian Mountains. Reaching the plains, the mountain streams form three major inland rivers, from East to West: the Shiyang, the Hei and the Shule River (see Figure 1). The hydro-geology of the river basins is similar (Zhou, Nonner, & Li, 2007). The plains are underlain with both shallow and deep high-storage aquifers. The shallow aquifers are shaped by unconsolidated sediments and are directly connected to the river flow (Ji et al., 2006).

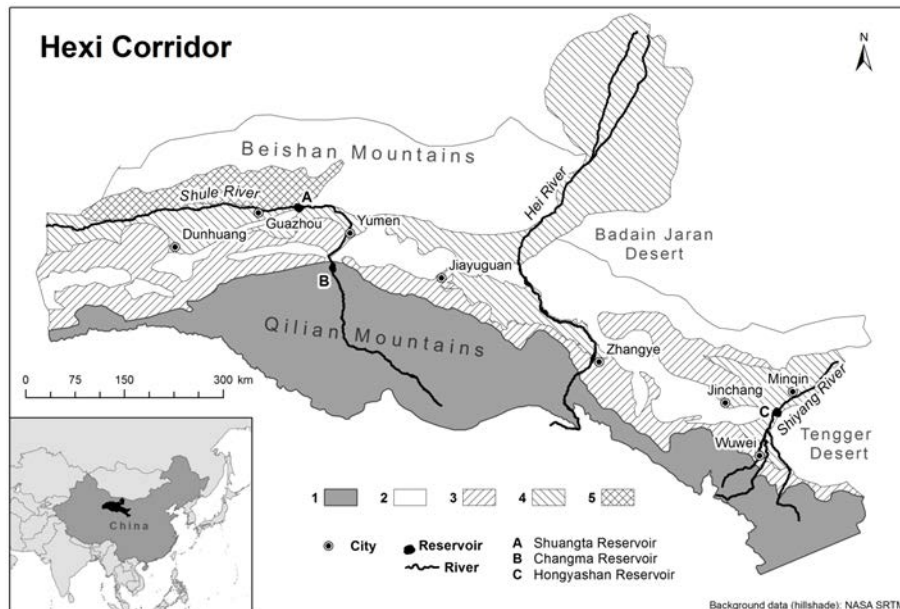


Figure 1 Map of the Hexi Corridor

1= high rock mountains, 2= low rock hills, 3= alluvial fans, 4= alluvial plains, 5= foothill plains

Source: made by Ronald Kraemer, adapted from Zhou et al. (2007)

Minqin and Guazhou County are both located at the downstream reaches of the inland rivers: Minqin in the Shiyang River Basin and Guazhou in the Shule River Basin. In these areas groundwater is easily accessible, although salinity levels increase upon intensive use (Wang, Ding, Shen, & Lai, 2003). Both counties contain vast areas of desert land, at least 90% of their total area. Annual rainfall in Minqin lies around 130 mm and evaporation at 2600 mm (Minqin County Government, 2015). Guazhou is even more arid, with annual rainfall around 50 mm and evaporation of 3100 mm (Gansu Land Resources Bureau, 2015).

The population density in Minqin (16 inhabitants/km²) is clearly higher than in Guazhou (6 inhabitants/km²). Macroeconomic conditions are fairly similar. Agriculture is the single most important economic sector in both counties. The sector is characterized by small scale family farming. Farmers produce a wide variety of crops; however, primarily cash crops, like cotton and melon, which are sold across China. As rainfall is low and evaporation is high, agriculture strongly relies on irrigation water. Due to the downstream location, farmers in Minqin and Guazhou have limited access to surface water and thus heavily depend on groundwater resources. In both areas groundwater use for irrigation developed over the last decades of the 20th century. Though some government support was available initially, eventually all groundwater wells were owned and managed by the farmers themselves. Until the early 2000s groundwater use was virtually not regulated by the government and intensified rapidly. At the same time shallow groundwater is the main water source for the natural vegetation in both areas. Falling groundwater tables easily lead to dying vegetation and increased desertification rates.

Except for the population density, the two counties are very much alike in their hydro-geological, climatic and macroeconomic conditions. Therefore, the two counties provide good comparable cases to study the impact of different regulatory institutions on farmers' groundwater use.

2.2 *Data Collection and Analysis*

This research is based on primary data collected in 2013 and 2014 in the study area. A survey on surface water and groundwater use and management was carried out by a team of experienced enumerators. A stratified random sample was selected to make sure different irrigation districts within the counties are represented. In Minqin, 105 farm households participated in the survey, spread across 10 villages in 5 different townships (representing 4% of the in total 249 rural villages in the county). In Guazhou, 44 farm households were interviewed, spread over 4 villages in 2 different townships (representing 5% of the in total 73 rural villages in the county). Respondents were asked to report their water use and cropping activities for the previous cropping season and describe water use and crop choice trends over the last ten years (see Appendix). In both areas the new regulatory institutions started to be introduced in 2007 and had become fully effective at least by 2010. By asking farmers' perception on changes over the last 10 years it was possible to assess the impact of the regulation measures without making direct reference to those measures and avoiding a socially desirable response. The survey also included a village leader questionnaire and a well operator questionnaire in every village to collect information on the (ground-) water management institutions and physical groundwater use conditions at village level. In both counties, the village leaders also function as leaders of the Water Users' Association (WUA). The WUA boundaries overlay the village boundaries. After a preliminary analysis of the survey data, a follow-up field visit was organized during which the lead author conducted in-depth interviews with water managers from irrigation district to river basin level, village leaders, well operators and farmers in the study area. In total 16 people were formally interviewed. The in-depth interviews were used to explain irregularities in the survey data and to better understand specific management institutions. Due to time constraints of the enumerator team, the survey was conducted over two years. In Minqin, the survey was carried out in 2013, collecting water use data for 2012. In Guazhou, the survey was carried out in 2014, collecting water use data for 2013. As the time lapse consists of only one year, it is assumed that changes in external factors which might influence farmers' decision making, like input and output prices, are fairly negligible.

In this article the primary data are used to describe the groundwater use and management situation in the two areas. All information was cross-checked by consulting multiple

sources (i.e. answers from the village leader, well operator and household questionnaires were triangulated and verified during subsequent in-depth interviews when irregularities occurred). In every case the following is described in detail: 1) the underlying motivation of local authorities to regulate groundwater; 2) how the respective regulatory institutions have been implemented; and 3) the outcome in terms of farmers' groundwater use quantity. The effectiveness of the respective regulatory institutions (i.e. whether they induced a reduction in groundwater use) is evaluated in two ways. The first is by assessing approximate changes in farmers' groundwater use quantity after the new regulation was implemented. Because accurate panel data is missing, the assessment is based on farmers' own perception of groundwater use trends over the last ten years. Second, the two regulatory institutions are evaluated by comparing farmers' current groundwater use quantities and related decisions (such as surface water use, crop choice and cropping area) between the two cases. Though implementation might have taken place at different rates, the regulatory institutions were fully implemented in both counties at the year of survey. In absence of more accurate water use data, each household's average number of surface water and groundwater irrigation turns is calculated per unit of land based on the survey data. For example, if a farmer has one crop on 2 ha of land irrigated with 3 irrigation turns ($2 \times 3 = 6$) and another crop on 4 ha of land irrigated with 6 irrigation turns ($4 \times 6 = 24$) the average number of irrigation turns is 5 ($30/6 = 5$). Fan et al. (2014) also used the reported number of irrigation water turns to calculate farmers' water use for different crops in Minqin. It is assumed that the number of irrigation turns roughly corresponds to the amount of water used per unit of land. Variation caused by the use of different irrigation methods can be considered small. Basically all farmers use flood irrigation (drip irrigation covers only 1% of the total irrigated area covered by the survey).

To examine the causal relation between the different regulatory institutions and farmers' groundwater use, additional external factors which could affect farmers' groundwater use in the study area are discussed. These include climatic, hydro-geological and macroeconomic conditions.

3 Results and Discussion

3.1 Minqin County

3.1.1 Motivation for Groundwater Regulation

In the 1970s and 1980s, Minqin County experienced a big tube well boom. By the end of the 20th century, thousands of irrigation wells had been drilled in Minqin and annual groundwater extraction was estimated to be around 600 million m³ (Gansu Province Water Resources Bureau, 2007). This clearly exceeded groundwater recharge through surface water inflow, which reached around 100 million m³ per year at the time (Zhang et al., 2011). In 2007, the Shiyang River Basin Management Plan was officially launched. This water policy reform was initiated to avoid further desertification and degradation of Minqin's environment (Wang, Zheng, & Wang, 2009). The project was financed by the central government and officially kicked-off by a visit of the then Chinese Prime Minister Wen Jiabao in 2007. The main target of the water re-allocation plan was to reduce Minqin's total groundwater use by almost 80% from 2005 to 2010 and more than double the surface water release to Minqin from the Hongyashan Reservoir (Wonderen, Pan, & Liu, 2008). The management plan is coordinated by the Shiyang River Basin Management Authority. Related surface water and groundwater management responsibilities are with the Water Resources Bureaus at prefecture and county level and implemented by the Irrigation District Bureaus (IDB) which usually have their offices in local towns. Below the province level the Chinese administration is divided into four levels: prefecture (or city), county, township and village. The Water Resources Bureaus follow the administrative boundaries of the prefectures and counties. The IDBs follow the boundaries of the canal irrigation districts and often include more than one township. At village level, the board of the Water Users' Association (WUA) takes over surface water and groundwater management tasks. Since the introduction of the Shiyang River Basin Management Plan, career opportunities for water officials in Minqin are linked to reaching the groundwater allocation targets. Rewarding officials for reaching environmental targets is a known instrument of the Chinese national government to ensure policy implementation at local level (Nickum, 2010).

To constrain farmers' groundwater use, the water authorities closed a large number of wells and restricted the pumping capacity of the remaining wells (Aarnoudse et al., 2012).

According to official records, 3000 out of 7000 tube wells were closed from 2007 to 2009. At the same time smart card machines were installed on the remaining wells to enforce a per capita groundwater quota system. The quotas were gradually implemented and became officially fully effective in 2010 (Aarnoudse et al., 2012). By the time of the interviews, well operators reported that in 2012 earlier problems had been solved and all wells were provided with functioning smart card machines.

3.1.2 Implementation of the Groundwater Quota

The official per capita water use quota is 1200 m³/year. (In the downstream irrigation districts where evaporation rates are higher the official water quota is slightly higher.) The quota is calculated based on a norm of 2.5 mu of irrigated crop land per person (1 mu is 0.066 ha). Before the water reforms, the per capita irrigated land was estimated to be around 5 mu (Gansu Province Water Resources Bureau, 2007). According to calculations by the local water authorities on crop irrigation requirements under conventional irrigation techniques and local climatic conditions the quota is expected to be sufficient for low water demanding, drought resistant crops, such as cotton (300 m³/mu) and sunflower (445 m³/mu) (Minqin Water Resources Bureau, 2009). The per capita water quota is set to realize a significant reduction in farmers' groundwater use, while safeguarding basic livelihood conditions for farmers. The water quota includes surface water, groundwater and rainfall. Priority is given to surface water allocation, which means that the actual groundwater quota can differ per year and per location depending on the surface water availability and rainfall during the cropping season. Farmers pay a groundwater fee of 0.02 CNY/m³ to the IDB, based on their actual groundwater use. This fee is mainly meant for cost recovery. Many farmers indicated that they are willing to pay a higher price for more water; however, the quotas are restrictive, and selling water to fellow farmers for a higher price is illegal. An electricity fee of 0.4 CNY/kWh for groundwater pumping is separately paid to the electricity provider. In Minqin, groundwater use is organized at sub-village level in farm groups of approximately 40 households. (Villages are usually divided into smaller units. In China different names circulate referring to the sub-village units, such as natural village, community, [production] team and small group [*ziran cun*, *she*, *dui* and *xiao zu*, respectively]. In this article the sub-village units are consistently referred to as farm groups.) In every farm group two to seven tube wells are in use. Like elsewhere in China, the shared ownership and use of wells is associated with collective institutions

inherited from the former production teams (Bluemling, Pahl-Wostl, Yang, & Mosler, 2010). Although the water quotas are officially calculated per person, the implementation is adapted to this reality. The groundwater quota is administered per farm group by the local IDB. The WUA reports the number of inhabitants per farm group to the IDB, based on which the water quota per farm group can be calculated. In order to control farmers' groundwater use during the cropping season, the groundwater is usually prepaid before an irrigation turn. A representative of the farm group needs to visit the IDB office to reload the card before each irrigation turn. This allows the IDB to adjust farmers' groundwater quota to the annual surface water and rainfall conditions. When a farm group has just received an extra surface water turn, they may have to skip the next groundwater turn. Fair distribution of the groundwater between the households is secured through collective institutions at farm group level (Aarnoudse, Herzfeld, Bluemling, & Qu, 2015).

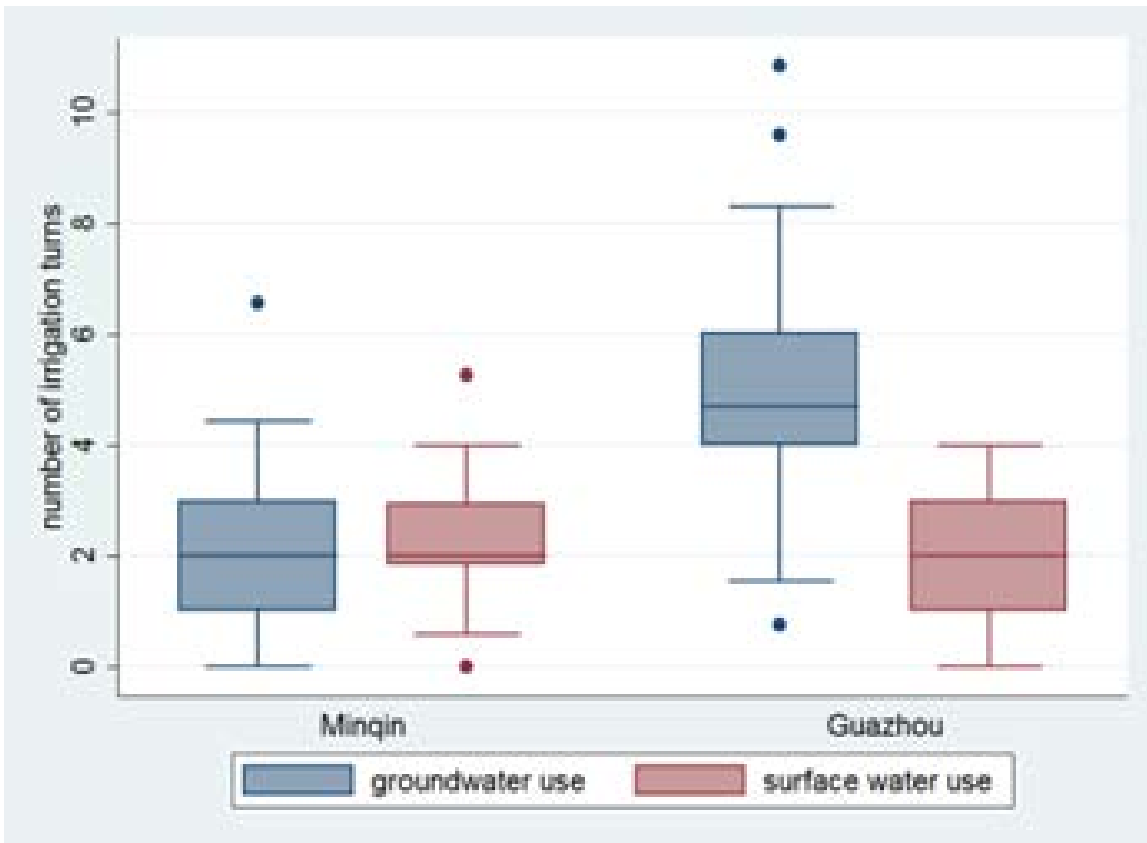


Figure 1 Distribution of groundwater and surface water use per household in Minqin (n=105) and Guazhou (n=44)

Household averages are based on the number of irrigation turns reported per crop and per cropping area.
Source: own survey

Table 1 Water use characteristics for most important crops in Minqin and Guazhou

County	Crop	n	% of cropping area	Surface water use (no. of turns)		Groundwater use (no. of turns)	
				Mean	Std. dev.	Mean	Std. dev.
Minqin	Cotton	77	32	2.0	1.1	1.9	1.2
	Sunflower	63	22	2.3	1.1	2.0	1.2
	Maize	68	17	2.3	1.2	2.6	1.3
	Fennel	35	12	2.4	1.0	1.5	0.9
Guazhou	Cotton	34	60	2.1	1.2	3.9	1.7
	Melon	35	37	1.6	1.4	6.1	3.0

Source: own survey

3.1.3 Farmers' Groundwater Use

Typically farmers in Minqin use both surface water and groundwater to irrigate their crops. Usually surface water is applied during the early cropping season and groundwater during the late cropping season. During the surveyed cropping season, farmers applied on average 2.2 groundwater turns and 2.2 surface water turns (see Figure 2). The mean cropping area per household is only 0.89 ha. The main crops are cotton, sunflower, maize and fennel (see Table 1). Whether the official per capita water quotas are complied with in reality is hard to evaluate based on the survey data. However, all interviewed village leaders and well operators claimed that the farmers reduced their groundwater use after the smart card machines have been installed. One village leader explained that they currently pump three times less groundwater than they used to. Moreover, 80% of the farmers stated that their groundwater use per unit of land had decreased over the last 10 years - i.e. since the machines were installed (see Figure 3).

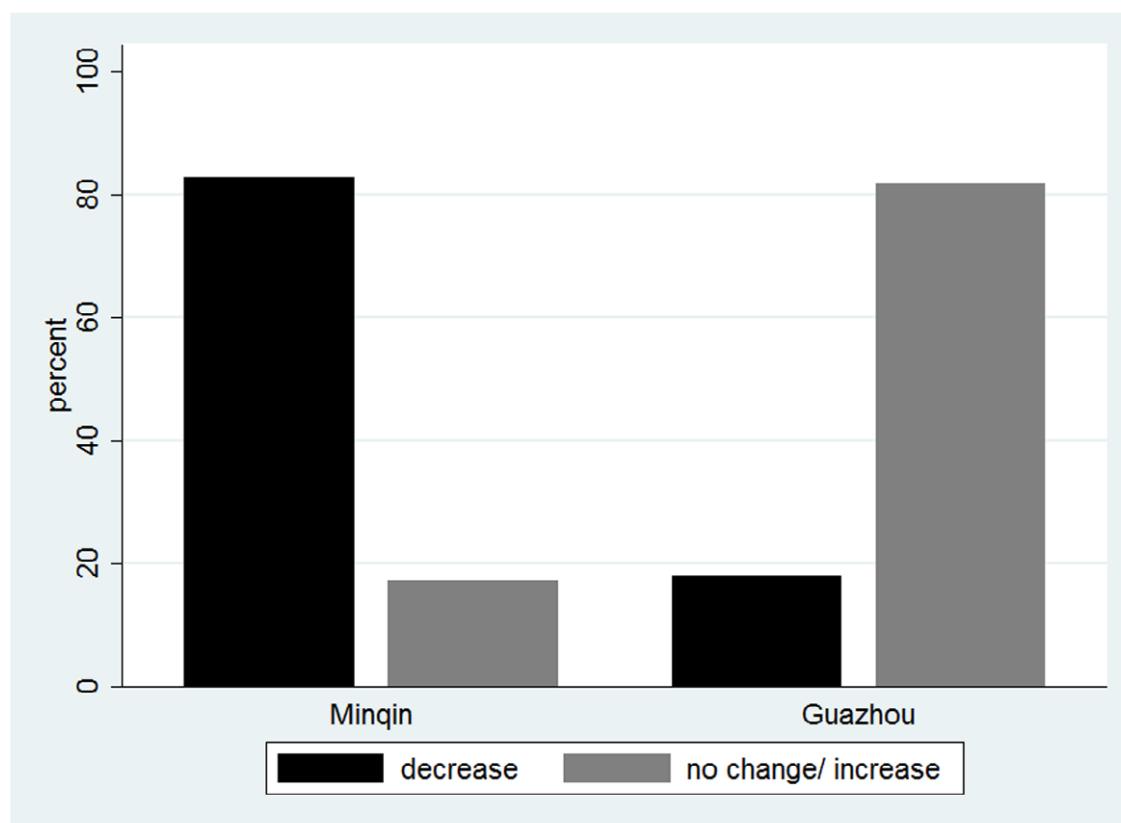


Figure 2 Farmers' perception on groundwater use trends in Minqin (n=105) and Guazhou (n=44)

Response to the question: How did your groundwater use quantity per unit of land change over the last 10 years?

Multiple choice answers: increase/ decrease/ no change.

Source: own survey

3.2 Guazhou County

3.2.1 Motivation for Groundwater Regulation

Groundwater use for irrigation started to develop in Guazhou County in the 1990s. At this time a large migration project brought rural inhabitants from central Gansu Province to the scarcely populated Shule River Basin (M. Zhang & Zhang, 1996). Through this project people were offered to escape from the resource poor and remote mountainous areas. In new settlements groundwater wells were drilled by the government to enable agriculture on previously uncultivated land. In the neighbouring, pre-existing settlements, groundwater drilling also took off around this time. At current there are around 2300 groundwater wells in use in the Shule River Basin. Annual groundwater extraction is estimated to be around 180 million m³, which is at least double the amount of annual groundwater recharge (Shule River Basin Management Bureau, 2013). Groundwater use in the basin takes place mainly in Guazhou County.

In 2005, a large water management reform in the Shule River Basin split the responsibilities on surface water and groundwater management over two separate government agencies. Groundwater management stayed with the local government administration and its Water Resources Bureaus at prefecture level and county level. Surface water management was transferred to a newly established River Basin Management Authority, which is under direct jurisdiction of the Provincial Government. Supervision over the Irrigation District Bureaus – previously in the hands of the Water Resources Bureaus – moved to the River Basin Management Authority. This shift in management responsibilities also meant that the surface water fees were now collected by the independent River Basin Management Authority.

It has been argued that irrigation water fees function as a new agricultural tax in China (Webber, Barnett, Finlayson, & Wang, 2008). In Guazhou, the surface water fee is currently 0.1 CNY/m³, which amounts up to 10-20 million CNY per year for the whole county. Soon after the local Water Resource Bureaus lost its revenue from surface water fees to the newly established River Basin Management Authority, the smart card machines were installed and the tiered groundwater pricing system was introduced. Before that time (since the revision of the national Water Law in 2002) an area based groundwater price had existed on paper, but was not effectively implemented. Officially the tiered pricing system intends to create economic incentives for farmers to save water (Government of Guazhou, 2015). However, the elimination of the income from surface water fees has likely increased the local government administration's interest in reinforcing the groundwater pricing system. Indeed, Yang et al. (2003) warn that groundwater pricing in China may create an incentive for local authorities to generate revenue.

3.2.2 Implementation of the Tiered Groundwater Pricing System

As in Minqin, households share ownership and use of groundwater wells per farm group. Farm groups consist approximately of 50 households, with four to seven wells per farm group. Although groundwater turns are often organised collectively – whereby the starting date is decided during a meeting of household heads – each farmer is responsible for irrigating his/her own plot. This means that how much water is used is primarily an autonomous decision made at household level. After installation of the smart card machines, the tiered groundwater pricing system was introduced in 2007. According to

the interviewed well operators all wells are currently equipped with smart card machines. Block rates are calculated per year per well. Village leaders and well operators reported the price to be 0.01 CNY per m³ for the first 100.000 m³ per well and 0.02 CNY per m³ above 100.000 m³. It is unclear based on what standard the price and volume of the initial consumption block is defined. One interviewed village leader estimated that up to 200.000 m³ are pumped per well. However, reported command areas per well differ between 10 and 40 ha, which means that total water use per well is also likely to vary. Moreover, well density between farm groups varies from four to seven wells per 50 households. So, because of the uneven well density between farm groups a block rate per well does not safeguard equal initial consumption blocks per household. In farm groups with a high well density individual users can pump more water for a low price than in farm groups with a low well density.

The functioning of the tiered pricing system is further blurred through the way the groundwater fee is paid and collected at farm group level. Usually the farm group puts a deposit on their shared groundwater account once and continues to use the well throughout the season i.e. the card does not have to be reloaded after each irrigation turn. The deposit is automatically charged based on the farm group's water use. Once the account is empty, the pump is turned off. After a new payment is made to the local Water Resources Bureau and the card is reloaded, the pump can be turned on again. The farm group's collective bill is paid by charging the individual households a groundwater price per hour or per kWh. The pumping hours or electricity use per household is recorded manually by the irrigators during each irrigation turn. The price includes both the electricity fee and the groundwater resource fee. The electricity fee is 0.4 CNY/ kWh for agricultural use purposes and collected separately by the electricity provider. The combined prices farmers mentioned were around 12 CNY/hour and around 0.65 CNY/kWh. In fact, many farmers are actually not aware of the exact groundwater price per m³ and do not differentiate rates for different levels of consumption. This means that the tiered pricing is not actually functional at household level, even though decisions on groundwater use quantities are made at this level.

Table 2 Characteristics of surveyed households in Minqin (n=105) and Guazhou (n=44).

	Minqin		Guazhou		Significance
	Mean	Std. dev.	Mean	Std. dev.	
Groundwater use (no. of turns)	2.2	1.2	5.0	2.0	***
Surface water use (no. of turns)	2.2	0.93	1.9	1.3	*
Total water use (no. of turns)	4.4	1.0	6.9	2.0	***
Irrigated area (ha)	0.89	0.34	2.2	1.3	***
No. of household members	4.6	1.1	4.1	1.3	**
Cotton yield (1000 kg/ha)	4.2	1.0	5.2	1.4	***
Average crop revenue (CNY 1000/ha)	28	22	35	13	**
Total crop revenue (CNY 1000)	27	35	81	60	***

*, **, *** significantly different from Minqin at the 10%, 5% and 1% level respectively.

Source: Own survey

3.2.3 Farmers' Groundwater Use

Most farmers in Guazhou use both surface water and groundwater to irrigate their crops. As in Minqin, surface water is applied during the early cropping season and groundwater during the late cropping season. During the surveyed cropping season, farmers applied on average 4.9 groundwater turns and 1.9 surface water turns (see Figure 2). The mean cropping area is 2.2 ha per household. The main crops are cotton and melon (see Table 1). In general farmers consider the groundwater price to be just fine or slightly expensive. However, they do not feel forced to reduce their groundwater use. Almost all village leaders and well operators think that the farmers did not change their groundwater use after the smart card machines have been installed. Eighty per cent of the farmers in Guazhou attested to using the same amount or more of groundwater per unit of land compared to ten years ago, i.e. before the machines were installed (see Figure 3).

3.3 Comparing the two cases

In both Minqin and Guazhou groundwater pumping for agriculture used to exceed groundwater recharge rates by far. Hence, China's national water law legitimates local authorities' constraining farmers' groundwater use in both counties. Nevertheless, the underlying motivations of the local authorities to install smart card machines and implement groundwater regulation measures differ strongly. In Minqin, strict regulation of farmers' groundwater use was supported by the national government and a groundwater allocation plan was set at river basin level. Under these circumstances reaching the groundwater allocation targets is rewarded with future career opportunities, which strengthens the incentives of the local water officials to reach those targets. In Guazhou,

the decision to reform the groundwater regulations was made at prefecture level, and not backed up by a groundwater allocation plan. The fact that the implementation of the new groundwater pricing system coincided with the elimination of income from surface water fees for the local government suggests that revenue generation was an important underlying motivation to establish the groundwater pricing system. One of the reasons why the national government has paid more attention to the case of Minqin is probably the severity of the problem. In Minqin the duration and intensity of groundwater overexploitation have been more pronounced than in Guazhou so far.

The underlying motivations of the local water authorities have had an impact on the choice and implementation of the regulatory institutions. In Minqin, quotas are calculated based on a maximum irrigated area per capita representing half of the previous mean irrigated area per capita. The design of the quota system allows for the restrictions of pumping rates, while securing equal access across farm groups. Furthermore, collective institutions at farm group level facilitate a fair distribution between households (Aarnoudse et al., 2015). Farmers' in Minqin indicate that they are willing to pay a higher price for more groundwater, but the quota system restricts their groundwater use. In Guazhou, the design of the tiered pricing system fails to allow equal initial consumption blocks for all farmers, due to the uneven distribution of wells across farm groups. The threshold within the tiered pricing system is further blurred by the practice of converting groundwater fees and electricity fees into a combined flat rate at farm group level. On top of that, the level of the groundwater fee does not seem to stimulate farmers to reduce their groundwater use. This supports the idea that the local Water Resources Bureau may be interested in keeping farmers' groundwater use at elevated levels to assure their own revenue from groundwater fees. As pointed out by Yang et al. (2003), raising prices to a level which will actually reduce farmers' groundwater use, would potentially also curtail their own revenue.

The circumstances under which the groundwater regulation measures have come about are also reflected by the actual impact these measures have had on farmers' groundwater use. Based on the survey respondents' perception of farmers' groundwater use in Minqin, groundwater use seems to have decreased since the implementation of the quota, while groundwater use in Guazhou seems to have increased despite the tiered groundwater pricing. Though these trends in groundwater use may depend not only on regulatory institutions but also on other factors, such as changes in surface water supply over the last

ten years, it does assert that the quotas have been more effectively implemented than tiered pricing. Moreover, the impact of the respective institutions on farmers' groundwater use is supported by the observations of farmers' current groundwater use in the two counties (i.e. under full implementation of the regulation measures). Based on statistics derived from the household questionnaire, farmers' groundwater use per household in Guazhou is substantially larger than in Minqin (see Table 2). On the one hand, it can be observed that the irrigated area per household in Guazhou is more than twice that in Minqin, even though the household size is slightly smaller. This can be explained by the difference in population density as well as the recent closure of wells in Minqin, which forced farmers to abandon previously cultivated land (Aarnoudse et al., 2012). Yet, on the other hand, farmers in Guazhou apply about twice as many groundwater turns per unit of land as in Minqin, while farmers' surface water use quantity is almost the same in the two counties. This can partly be explained by the difference in climatic conditions. Based on average evaporation and rainfall data, one would expect the irrigation requirements for equivalent crops to be around 20% higher in Guazhou. (If crop characteristics are neglected and basic irrigation requirements are calculated as $\text{irrigation requirements} = \text{evaporation} - \text{rainfall}$, the ratio of Minqin:Guazhou would be 2470:3050.) However, the data show that the total number of irrigation turns (including surface water and groundwater) used per unit of land in Guazhou is almost 60% higher than in Minqin (see Table 2).

Moreover, comparing cropping patterns, the high groundwater use intensity allows farmers in Guazhou to grow melon as a major crop. Melon is a particularly large groundwater gobbler due to its frequent irrigation needs until late in the season. In Minqin, melon was a popular crop in the 1990s and early 2000s, but has largely disappeared recently. Most surveyed village leaders estimated that melon still made up 40% of their cropping area ten years ago. However in 2012, less than 5% of the surveyed farmers in Minqin reported growing melon, and this was basically for own consumption. Village leaders regard the groundwater restrictions as the main reason for this crop change. In contrast, melon production is a growing business in Guazhou. All village leaders stated that melon production has boomed over the last ten years. Furthermore, the crop water use data suggest that farmers in Guazhou obtain higher cotton yields due to additional groundwater use. On average, farmers in Guazhou apply two extra irrigation turns and obtain a 20% higher yield (see Table 2). Overall, farmers in Guazhou gain a higher

revenue from crop production than in Minqin, both per unit of land and in total (see Table 2). This indicates that the restricted access to groundwater is a limiting production factor for farmers in Minqin.

The question remains whether it is indeed the difference in regulatory institutions which primarily restricts farmers' access to groundwater in Minqin compared to Guazhou. Hydro-geological access conditions may also play a role. Although the natural hydro-geological conditions (i.e. without human alteration) in both counties can be considered similar, groundwater depth and salinity rates may differ depending on the duration and intensity of overexploitation. Based on groundwater depths reported by well operators and village leaders, it can be assumed that in Minqin the groundwater level is between 20 to 40 meters, while in Guazhou it is between 10 to 20 meters. This means that energy consumption per m³ of pumped groundwater is expected to be a little higher in Minqin. However, as pointed out by Hoogesteger and Wester (2015), once tube wells are in place the threshold at which farmers' access to groundwater becomes critically threatened is at much deeper groundwater levels (>100 m). With regard to the groundwater salinity, the exact salinity rates in the two counties could not be obtained through the survey, however; the groundwater salinity problem is perceived similarly in both counties. In general, groundwater is considered more saline than surface water, which is the main reason for farmers to prioritize surface water irrigation (when available). Moreover, in about one-third of the villages in each county, well operators and village leaders assessed the groundwater salinity as high (i.e. selecting 4 or 5 on a scale from 1 to 5). Thus, groundwater salinity is perceived as a problem in both counties, presumably with locally varying levels of severity. This means that groundwater salinity may be a reason for farmers to reduce their groundwater use, but if so this would appear in both counties. All in all, the most flagrant difference in farmers' access to groundwater between Minqin and Guazhou is determined by the institutional conditions, as illustrated in this article.

3.4 Quota versus Tiered Pricing

The observed difference in impact on farmers' groundwater use cannot simply be ascribed to a theoretical understanding of the different types of regulatory institutions and the underlying allocation mechanisms. In fact the societal context had a major influence on the choice of regulatory institutions and the way they have been implemented. Although

in both counties the official reason to install smart card machines was to regulate intensive groundwater use, the water authorities' incentives to actually curb farmers' groundwater use has been more pronounced in Minqin than in Guazhou. The strong motivation to reach groundwater allocation targets has likely caused the authorities in Minqin to select quotas rather than pricing as a regulation measure. This is in line with Molle's (2009) observations on surface water irrigation management. He argues that to deal with issues of water scarcity authorities are more likely to fall back on water quotas than water pricing. In Guazhou, the need to actually reduce farmers' groundwater use was less pressing. The actual reason for the new groundwater pricing system seems to have been a loss of income from surface water fees. Yang et al. (2003) earlier warned that revenue generation by local authorities may pervert the functioning of groundwater fees as an appropriate instrument to regulate farmers' groundwater use in China. Moreover, Zhou, Wu, & Zhang (2015) calculated that groundwater prices need to be extraordinary high to actually affect farmers' groundwater use decisions in the context of the Hexi Corridor, which undermines the political feasibility of groundwater pricing as a regulation measure.

The different underlying motivations also become apparent through the way the regulatory institutions have been implemented. The way the per capita quota is calculated in Minqin clearly aims at an equal reduction in groundwater use for all users. During the implementation process the per capita quota is transferred into a "bulk" quota for farm groups with shared well ownership. However, it is argued that the fair distribution of groundwater quota between households is supported by collective institutions at farm group level (Aarnoudse et al., 2015). In contrast, the implementation of a block rate per well in Guazhou fails to structurally incorporate the aspects of reduced groundwater use and equal initial consumption blocks for all users due to the uneven distribution of wells. This situation is even more precarious taking into account that a careful design is regarded critical to achieve efficient resource allocation through a tiered pricing system (Schoengold & Zilberman, 2014). On top of that, the way groundwater fees are collected at household level in Guazhou blurs the effect of a pricing threshold, which is the theoretical idea behind tiered groundwater pricing. Molle (2009) pointed at the same risk for irrigation water pricing when surface water is allocated in bulk quantities to multiple users.

4 Conclusions

This article compared the groundwater management cases of Minqin and Guazhou Counties in north-west China. The two counties are both characterised by intensive groundwater use for small scale agriculture. Over the last decade smart card machines – water meters linked to a digital administration system – have been installed on farmers’ pumping installations in both study areas; however, the regulatory institutions behind the use of those machines differ significantly. In Minqin, the smart card machines have primarily been used to implement a per capita groundwater quota. In Guazhou, the technology has been used to implement a tiered groundwater pricing system. It is argued that in Minqin the local authorities were persuaded by higher authorities to reduce farmers’ groundwater use, while in Guazhou new groundwater policies have rather been driven by an interest in compensating lost revenue from surface water fees. The way the quota system is implemented aims more directly at a reduction of farmers’ groundwater use, whereas the practical implementation of the tiered groundwater fees has too many flaws to actually function as a regulatory measure. In Minqin, farmers indeed claim to have reduced their groundwater use since the implementation of the quota, while in Guazhou farmers consider to have increased their groundwater use over the last ten years despite the introduction of the tiered groundwater price. Moreover, farmers’ current groundwater use in Minqin is substantially lower than in Guazhou, even though the climatic and hydro-geological conditions are fairly similar. Based on these observations it is concluded that in the given context the groundwater quota has been more effective than tiered groundwater pricing in curbing farmers’ groundwater use.

The experience with smart card machines for groundwater management in north-west China has important implication for other regions where the regulation of intensified groundwater use for small-scale agriculture poses a problem. It shows that the usefulness of smart card machines varies depending on their embedding in a certain societal context, related regulatory institutions and their implementation. The example presented in this article illustrates that a quota system is more likely to aim at and attain a reduction in groundwater use, whereas tiered groundwater pricing can be implemented without any impact on farmers’ groundwater use behaviour. Prices high enough to actually affect farmers’ groundwater use decisions are necessarily considered desirable by local authorities. Although smart card machines may provide a technological solution for the

groundwater monitoring problem, they do not automatically remove all obstacles to effective groundwater regulation. Other important obstacles, such as a lack of support by local authorities, may continue to hinder effective groundwater regulation.

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References

- Aarnoudse, E., Bluemling, B., Wester, F., & Wei, Q. (2012). The role of collective groundwater institutions in the implementation of direct groundwater regulation measures in Minqin County, China. *Hydrogeology Journal* 20(7), 1213-1221. doi: 10.1007/s10040-012-0873-z
- Aarnoudse, E., Herzfeld, T., Bluemling, B., & Qu, W. (2015). *Shared well ownership provides grounds for collective action in Northwest China*, *Global Water Forum*. Retrieved from <http://www.globalwaterforum.org/2015/02/09/shared-well-ownership-provides-grounds-for-collective-action-in-northwest-china/>
- Bjornlund, H., Nicol, L., & Klein, K. K. (2007). Challenges in implementing economic instruments to manage irrigation water on farms in southern Alberta. *Agricultural Water Management*, 92(3), 131-141. doi: 10.1016/j.agwat.2007.05.018
- Bluemling, B., Pahl-Wostl, C., Yang, H., & Mosler, H.-J. (2010). Implications of Stakeholder Constellations for the Implementation of Irrigation Rules at Jointly Used Wells—Cases from the North China Plain, China. *Society & Natural Resources*, 23(6), 557-572. doi: 10.1080/08941920903376998
- Calow, R. C., Howarth, S. E., & Wang, J. (2009). Irrigation Development and Water Rights Reform in China. *International Journal of Water Resources Development*, 25(2), 227-248. doi: 10.1080/07900620902868653
- De Stefano, L., & Lopez-Gunn, E. (2012). Unauthorized groundwater use: institutional, social and ethical considerations. *Water Policy*, 14, 147-160. doi: 10.2166/Wp.2012.101
- Fan, Y., Wang, C., & Nan, Z. (2014). Comparative evaluation of crop water use efficiency, economic analysis and net household profit simulation in arid Northwest China. *Agricultural Water Management*, 146, 335-345. doi: 10.1016/j.agwat.2014.09.001
- Gansu Land Resources Bureau. (2015). Guazhou xian guotu ziyuan ju: Dili gaikuang [Guazhou County Land Resources Bureau: Geographic overview]. <http://www.gsdlr.gov.cn/jqgzx/content.aspx?id=ARTI396>
- Gansu Province Water Resources Bureau. (2007). *Shiyang he liuyu zhongdian zhili guihua [Shiyang River Basin Management Plan]*. Retrieved from <http://www.sdpc.gov.cn/fzgggz/fzgh/ghwb/gjjgh/200806/P020150630514361951622.pdf>
- Government of Guazhou. (2015). *Guazhou xian dixiashui ziyuan guanli banfa [Groundwater Management in Guazhou County]*. Retrieved from <http://www.guazhou.gov.cn/ReadNews.asp?NewsID=43855>
- Hoogesteger, J., & Wester, P. (2015). Intensive groundwater use and (in)equity: Processes and governance challenges. *Environmental Science & Policy*, 51(0), 117-124. doi: 10.1016/j.envsci.2015.04.004
- Ji, X. B., Kang, E. S., Chen, R. S., Zhao, W. Z., Zhang, Z. H., & Jin, B. W. (2006). The impact of the development of water resources on environment in arid inland river basins of Hexi region, Northwestern China. *Environmental Geology*, 50(6), 793-801. doi: 10.1007/s00254-006-0251-z
- Kendy, E., Zhang, Y., Liu, C., Wang, J., & Steenhuis, T. (2004). Groundwater recharge from irrigated cropland in the North China Plain: case study of Luancheng County, Hebei Province, 1949–2000. *Hydrological Processes*, 18(12), 2289-2302. doi: 10.1002/hyp.5529
- Li, P., Qian, H., Howard, K. W. F., & Wu, J. (2015). Building a new and sustainable “Silk Road economic belt”. *Environmental Earth Sciences*, 74(10), 7267-7270. doi: 10.1007/s12665-015-4739-2
- Liu, C. L., Yang, W., & Wang, J. (2009). Jijing guangai jiliang shoufei guanli yu kongzhi xitong yanzhi [Research on Management and Control System for Charge and Measuring of Well Irrigation] *Jieshui guangai [Water Saving Irrigation]*(06), 55-57
- Liu, C. M., Yu, J., & Kendy, E. (2001). Groundwater Exploitation and Its Impact on the Environment in the North China Plain. *Water International*, 26(2), 265-272. doi: 10.1080/02508060108686913

- Madani, K., & Dinar, A. (2013). Exogenous regulatory institutions for sustainable common pool resource management: Application to groundwater. *Water Resources and Economics*, 2-3, 57-76. doi: 10.1016/j.wre.2013.08.001
- Minqin County Government. (2015). Minqin qingkuang [Situation of Minqin]. http://www.minqin.gansu.gov.cn/Category_245/Index.aspx
- Minqin Water Resources Bureau. (2009). *Shiyang he liuzu shuiziyuan guanli guihua: Minqin xian shui quan shui jia gaige guanli fa* [Shiyang River Basin Management Plan: Minqin County Water Rights and Water Price Reform].
- Molle, F. (2009). Water scarcity, prices and quotas: a review of evidence on irrigation volumetric pricing. *Irrigation and Drainage Systems*, 23(1), 43-58. doi: 10.1007/s10795-009-9065-y
- Nickum, J. E. (2010). Water Policy Reform in China's Fragmented Hydraulic State: Focus on Self-Funded/Managed Irrigation and Drainage Districts. *Water Alternatives*, 3(3), 537-551
- Schoengold, K., & Zilberman, D. (2014). The economics of tiered pricing and cost functions: Are equity, cost recovery, and economic efficiency compatible goals? *Water Resources and Economics*, 7, 1-18. doi: 10.1016/j.wre.2014.07.002
- Shah, T. (2007). The groundwater economy of South Asia: an assessment of size, significance and socio-ecological impacts. In M. Giordano & K. G. Villholth (Eds.), *The agricultural groundwater revolution: Opportunities and threats to development* (pp. 7-36). Wallingford: Cabi.
- Shen, D. (2015). Groundwater management in China. *Water Policy*, 17(1), 61-82. doi: 10.2166/wp.2014.135
- Shule River Basin Management Bureau. (2013). *Qianyi shule he liuyu shui ziyuan baohu yu kaifa* [Water resources conservation and development in the Shule River Basin].
- Wada, Y., Beek, v., Ludovicus P. H., Kempen, v., Cheryl M., Reckman, J. W. T. M., Vasak, S., & Bierkens, M. F. P. (2010). Global depletion of groundwater resources. *Geophysical Research Letters*, 37(20), L20402. doi: 10.1029/2010gl044571
- Wang, G., Ding, Y., Shen, Y., & Lai, Y. (2003). Environmental degradation in the Hexi Corridor region of China over the last 50 years and comprehensive mitigation and rehabilitation strategies. *Environmental Geology*, 44(1), 68-77. doi: 10.1007/s00254-002-0736-3
- Wang, J. X., Huang, J., Rozelle, S., Huang, Q., & Zhang, L. (2009). Understanding the water crisis in Northern China: what the government and farmers are doing. *Water Resources Development*, 25(1), 141-158. doi: 10.1080/07900620802517566
- Wang, J. X., Huang, J. K., Huang, Q. Q., & Rozelle, S. (2006). Privatization of tubewells in North China: Determinants and impacts on irrigated area, productivity and the water table. *Hydrogeology Journal*, 14(3), 275-285. doi: 10.1007/s10040-005-0482-1
- Wang, J. X., Huang, J. K., Rozelle, S., Huang, Q. Q., & Blanke, A. (2007). Agriculture and groundwater development in northern China: trends, institutional responses, and policy options. *Water Policy*, 9, 61-74. doi: 10.2166/Wp.2007.045
- Wang, Z., Zheng, H., & Wang, X. (2009). A Harmonious Water Rights Allocation model for Shiyang River Basin, Gansu Province, China. *International Journal of Water Resources Development*, 25(2), 355-371. doi: 10.1080/07900620902868836
- Webber, M., Barnett, J., Finlayson, B., & Wang, M. (2008). Pricing China's irrigation water. *Global Environmental Change*, 18(4), 617-625. doi: 10.1016/j.gloenvcha.2008.07.014
- Wonderen, v., J., Pan, C. X., & Liu, Z. P. (2008). *Can the Silk Road oasis be sustained?*. BHS 10th National Hydrology Symposium Exeter.
- Yang, H., Zhang, X., & Zehnder, A. J. B. (2003). Water scarcity, pricing mechanism and institutional reform in northern China irrigated agriculture. *Agricultural Water Management*, 61(2), 143-161. doi: 10.1016/s0378-3774(02)00164-6

- Zhang, M., & Zhang, Z. (1996). Assessment of the overall effect of migration: the Hexi corridor irrigation and migrant settlement project. *Chinese journal of population science*, 8(2), 143-149
- Zhang, Y., Ma, J., Chang, X., Wonderen, v., J., Yan, L., & Han, J. (2011). Water resources assessment in the Minqin Basin: an arid inland river basin under intensive irrigation in northwest China. *Environmental Earth Sciences*, 1-9. doi: 10.1007/s12665-011-1165-y
- Zhen, L., & Routray, J. K. (2002). Groundwater Resource Use Practices and Implications for Sustainable Agricultural Development in the North China Plain: A Case Study in Ningjin County of Shandong Province, PR China. *International Journal of Water Resources Development*, 18(4), 581-593. doi: 10.1080/0790062022000017419
- Zhou, Y., Nonner, J. C., & Li, W. (2007). *Strategies and techniques for groundwater resources development in Northwest China*: China Land Press Beijing.
- Zhou, Q., Wu, F., & Zhang, Q. (2015). Is irrigation water price an effective leverage for water management? An empirical study in the middle reaches of the Heihe River basin. *Physics and Chemistry of the Earth, Parts A/B/C*, 89–90, 25–32. doi:10.1016/j.pce.2015.09.002.

Appendix: Main survey questions on farmers' water use and cropping activities.

	Questions	Multiple choice answers
Household questionnaire	What crops did you grow during the previous cropping season? • Please report per crop: cropping area (mu); number of plots cultivated; yield (kg/mu); number of surface water irrigations turns; number of groundwater irrigation turns; and area irrigated with drip irrigation (mu). Did your household's cropping area change over the last ten years?	yes/ no
	• If yes, what was the original cropping area (mu)? • What has been the reason for this change? Did your household's water use quantity per mu change over the last ten years? • If yes, how did the groundwater use change? • How did the surface water use change? • What has been the reason for this change?	yes/ no increase / decrease / no change increase / decrease / no change
Village leader questionnaire	What has been the village's total cropping area during the previous cropping season (mu)? What crops were grown during the previous cropping season? • Please report the cropping area per crop (mu). How many surface water irrigation turns did the village receive during the previous cropping season? • Please report per irrigation turn: starting date; number of days water was supplied; and water volume (m³). Compared to ten years ago, today's cropping area is:	much larger / a little larger / more or less the same size / a little smaller / much smaller
	• When known, please report the village's total cropping area ten years ago (mu). • If a change occurred, what has been the reason for this change? What crops were grown in the village ten years ago? • When known, please report the cropping area per crop (mu). • If a change occurred, what has been the reason for this change? How has today's surface water supply quantity changed compared to ten years ago? Did the surface water-groundwater use ratio for irrigation in the village change over the last ten years? • If yes, what used to be the situation ten years ago? Ten years ago farmers used:	increase / decrease / no change yes/no only surface water / only groundwater / both, but more/less surface water, more/less groundwater
	• What has been the reason for this change? What is the total number of groundwater wells in the village? Have smart card machines been installed on the wells in the village? • If yes, what part of the wells has been provided with smart card machines (%)? • How do you think farmers' groundwater use quantity has changed since the installation of the smart card machines?	yes/no decreased a lot / decreased a little / more or less the same / increased a little / increased a lot
	How many wells were in use in the farm group during the previous cropping season?	

Well operator questionnaire	<ul style="list-style-type: none"> • Please report per well: decade in which the well was drilled; well ownership; irrigation command area (mu); well depth (m); water depth in well (m); level of groundwater salinity (1–5); and presence of a functioning smart card machine (yes/no). 	
	How do you think farmers' groundwater use quantity has changed since the installation of the smart card machines?	decreased a lot / decreased a little / more or less the same / increased a little / increased a lot