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Controlling Groundwater through Smart Card Machines:

The Case of Water Quotas and Pricing Mechanisms in Gansu Province, China

Eefje Aarnoudse and Bettina Bluemling

Groundwater issues addressed

- ✓ Groundwater over-abstraction
- ☐ Groundwater quality/human health
- ☐ Salinity issues/intrusion
- ☐ Land subsidence
- ✓ Ecosystem degradation
- ✓ Food security/livelihoods

Type of interventions

- ✓ Legal initiative/regulation
- ✓ Policy
- ✓ Technology application
- ☐ Local initiative

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GROUNDWATER SOLUTIONS INITIATIVE FOR POLICY AND PRACTICE

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Front cover photograph: Groundwater well with smart card machine, Minqin County, China (*photo*: Eefje Aarnoudse).

About the Groundwater Solutions Initiative for Policy and Practice (GRIPP) Case Profile Series

The GRIPP Case Profile Series provides concise documentation and insight on groundwater solution initiatives from around the world to practitioners, decision makers and the general public. Each Case Profile report covers a contemporary intervention (innovation, technology or policy) or a series of applied groundwater management-related approaches aimed at enhancing groundwater sustainability from an environmental and socioeconomic perspective at local, national or international level. Integrated analysis of the approach, background, drivers, stakeholders, implementation, experiences and outcomes are discussed with a view to illustrating best practices, factors that could lead to success or failure, and wider applicability.

Abstract

English

Since the 1970s, intensive groundwater abstraction by smallholder farmers has led to falling groundwater levels and related problems in many parts of North China. The 2002 revised Water Law urges local authorities to regulate groundwater use in regions of overdraft. This GRIPP Case Profile documents two cases of local groundwater abstraction regulation in Gansu Province, Northwest China, based on primary data collection. In both cases, smart card machines were installed on farmers' wells to control groundwater abstraction. However, in the case of Minqin County, the local authorities opted for quotas, while in the case of Guazhou County, they opted for tiered water pricing as a regulation instrument. The quotas in Minqin have been implemented in a way that directly affected farmers' groundwater use practices. Consequently, farmers are no longer free to decide when and how much groundwater to use. The tiered water pricing in Guazhou has had little implications for farmers' individual groundwater use practices. The pricing threshold is flattened out at farm group level and the price is not raised to a level which instills behavioral change. Hence, it can be concluded that the potential of smart card machines to control groundwater abstraction is highly dependent on the design and implementation of the regulatory mechanism behind the machines. Although the present study cannot draw hard conclusions on the effectiveness of quotas and pricing mechanisms per se, it does provide an indication that, in the given societal context, the practicability of quotas to reduce farmers' groundwater abstraction is higher than that of tiered pricing. Notably, the case of Minqin exemplifies that quotas lend themselves well to ensure equitable water access to all farmers and maintain the buffer function of conjunctive surface water and groundwater use. These are important principles to design effective groundwater regulation policies, both in and outside China.

French

Depuis les années 1970, l'exploitation intensive des eaux souterraines par les petits exploitants agricoles a entraîné une baisse de niveau des eaux souterraines ainsi que d'autres problèmes liés dans de nombreuses régions du nord de la Chine. La loi sur l'eau révisée en 2002 exhorte les autorités locales à réglementer l'utilisation des eaux souterraines dans les régions à surexploitation. Ce GRIPP Case Profile documente, sur la base de la collecte de données primaires, deux cas de réglementation locale des prélèvements d'eaux souterraines dans la province de Gansu, dans le nord-ouest de la Chine. Dans les deux cas, des machines à cartes à puce ont été installées pour opérer les puits des agriculteurs et ainsi contrôler le captage des eaux souterraines. Cependant, dans le cas du Département de Minqin, les autorités locales ont opté pour des quotas, tandis que dans le cas du Département de Guazhou, elles ont opté pour une tarification différenciée de l'eau en tant qu'instrument de régulation. Les quotas à Minqin ont été mis en œuvre d'une manière qui a directement affecté les pratiques d'utilisation des eaux souterraines des agriculteurs. Par conséquent, les agriculteurs ne sont plus libres de décider quand et combien d'eau souterraine utiliser. La tarification progressive de l'eau à Guazhou a eu peu d'implications pour les pratiques individuelles d'utilisation des eaux souterraines des agriculteurs. Le seuil de prix est aplani au niveau de la ferme et le prix n'est pas élevé à un niveau qui puisse instiller un changement de comportement des agriculteurs. Par conséquent, on peut conclure que le potentiel des machines à cartes à puce pour contrôler l'abstraction des eaux souterraines dépend fortement de la conception et de la mise en œuvre du mécanisme de régulation qui accompagne les machines. Bien que la présente étude ne puisse tirer de conclusions définitives sur l'efficacité des quotas et des mécanismes de fixation des prix, elle indique que, dans un contexte sociétal donné, les contingents visant à réduire les prélèvements d'eau souterraine sont plus pratiques que les prix différenciés. Notamment, le cas de Minqin illustre le fait que les quotas se prêtent bien à assurer un accès équitable à l'eau pour tous les agriculteurs et maintenir la fonction tampon de l'utilisation conjointe des eaux de surface et des eaux souterraines. Ce sont des principes importants pour concevoir des politiques efficaces de régulation des eaux souterraines, en Chine et à l'étranger.

Spanish

Desde la década de los años setenta, la extracción intensiva de agua subterránea por parte de los pequeños agricultores ha conllevado la disminución de los niveles de agua subterránea y causado múltiples problemas relacionados en muchas partes del norte de China. La Ley de Aguas revisada en el 2002 insta a las autoridades locales a regular el uso del agua subterránea en regiones con sobre-explotación. Este GRIPP Case Profile, basado en la recopilación de datos primarios, documenta dos casos de regulación local de las extracciones de agua subterránea en la provincia de Gansu, en el noroeste de China. En ambos casos, se instalaron máquinas de tarjetas inteligentes en los pozos de los agricultores para controlar la extracción de agua subterránea. Sin embargo, en el caso del condado de Minqin, las autoridades locales optaron por cuotas, mientras que en el condado de Guazhou, optaron por los precios escalonados del agua como instrumento de regulación. Las cuotas en Minqin se han implementado de una manera que afecta directamente las prácticas de uso de agua subterránea de los agricultores. En consecuencia, los agricultores ya no tienen libertad para decidir cuándo y cuánta agua subterránea usar. El precio escalonado del agua en Guazhou ha tenido pocas implicaciones para las prácticas individuales de uso de agua subterránea de los agricultores. El umbral de fijación de precios se nivela a nivel de grupo de agricultores y el precio no se eleva a un nivel que inculque un cambio de comportamiento. Por lo tanto, se puede concluir que el potencial de las máquinas de tarjetas inteligentes para controlar la extracción de aguas subterráneas depende en gran medida del diseño y la implementación del mecanismo regulador que acompaña la instalación de las máquinas. Aunque el presente estudio no puede extraer conclusiones sólidas sobre la efectividad de las cuotas y los mecanismos de fijación de precios per se, sí indica que, en el contexto social dado, la viabilidad de las cuotas para reducir la extracción de agua subterránea de los agricultores es mayor que la de los precios escalonados. Notablemente, el caso de Minqin ejemplifica que las cuotas pueden asegurar el acceso equitativo del agua a todos los agricultores y mantener la función de amortiguación conjuntiva del agua de superficie y el uso del agua subterránea. Estos son principios importantes para diseñar políticas efectivas de regulación de las aguas subterráneas, tanto dentro como fuera de China.

Chinese

自20 世纪 70 年代以来，小农户大量抽取地下水，造成华北许多地区的地下水位下降，并引发了相关问题。2002年修订的《中国人民共和国水法》敦促地方主管部门对用水过度地区的地下水使用进行调控。本 GRIPP 案例简介通过收集原始数据，记录了中国西北甘肃省内调控当地地下水抽取的两个案例。在两个案例中，地方主管部门都在农户水井上安装了智能卡设备来控制地下水抽取。然而，在民勤县的案例中，地方主管部门选择了配额制；而在瓜州县的案例中，他们选择了阶梯水价作为调控方式。民勤县实行的配额制直接影响了农户的地下水使用行为。因此，农户不能再随意决定何时抽取以及抽取多少地下水。而瓜州县的阶梯水价对农户的个人用水行为影响不大。在农户集体层面，价格门槛被拉平，水价没有提升到能改变农户用水行为的水平。因此，我们可以得出结论：通过智能卡设备控制地下水抽取的可行性高度取决于设备背后调控机制的设计与实施。尽管当前的研究无法对配额制和定价机制本身的有效性得出确切结论，但它确实表明，在一定的社会背景下，对于减少农户的地下水抽取，配额制比阶梯价格更为实用。值得注意的是，民勤县的案例还表明配额制能有效确保所有农户的公平用水，并很好地保持了地表水和地下水联合使用的缓冲功能。这些都是中国内外在设计有效地下水调控政策时所遵循的重要原则。

1. Groundwater development and management in North China

North China is one of the world's most water-stressed regions in terms of the ratio of withdrawal to supply (Gassert et al. 2013; Sun et al. 2009; Wang et al. 2016b). Nevertheless, irrigated agriculture in the region is undergoing continued growth, primarily driven by groundwater pumping (Grogan et al. 2015; Guo et al. 2009; Liu and Feng 2015; Sun et al. 2009). China's groundwater withdrawals for agriculture, centered in the northern part of the country, was estimated to have reached 100 cubic kilometers per year around the year 2000, which accounts for about 13% of global groundwater withdrawals for irrigation (Wada et al. 2012). Groundwater irrigation based on motorized pumping took off in the early 1970s, accelerating after the redistribution of land-use rights to individual households and liberalization of the market in the late 1970s. Subsequent economic growth and increased demand for agricultural products provided incentives for smallholders to increase their income based on intensified groundwater use (Wang et al. 2006). At the same time, intensive pumping and falling groundwater levels have led to significant problems, such as land subsidence, saline intrusion in coastal areas and degradation of natural ecosystems (Kendy et al. 2004; Liu et al. 2001; Lohmar et al. 2003).

For a long time, groundwater management in China was characterized by a laissez-faire attitude of the water administration. Even though regulation measures existed officially (such as well permits or groundwater abstraction fees), they were not strictly enforced. Although groundwater resources were formally owned by the state, farmers experienced a virtually open-access situation. This applied until 1998, when a ministerial reform shifted the responsibility for groundwater abstraction management from the then Ministry of Geological and Mineral Resources to the Ministry of Water Resources. In 2002, the Ministry of Water Resources issued a revised Water Law, which, for the first time, stipulated the government to be responsible for groundwater regulation in regions in a state of overdraft (i.e., where groundwater withdrawals exceed recharge). As a first step, all groundwater use regions should be classified into different development zones depending on the level of overdraft (i.e., unrestricted, restricted and forbidden groundwater development zones) (Shen 2015). Yet, national directives on policy implementation with a focus on the restricted and forbidden development zones have not been formulated, leading to diverging local groundwater management situations and the use of different regulatory instruments to control abstraction across the country (Shen 2015).

The need for effective instruments for groundwater management in a context of intensive use for agriculture is widely acknowledged (Foster et al. 2008; Kemper 2007). Montginoul et al. (2016: 556) discussed five types of direct regulatory instruments for the management of groundwater abstraction: (i) command and control, (ii) abstraction tax systems, (iii) payment, (iv) tradable abstraction water rights, and (v) persuasion. Other types of instruments include indirect regulation through the energy or agriculture sector (Giordano 2009; Mukherji and Shah 2005). The effect of different regulatory instruments on groundwater levels and farming conditions can be analyzed with the use of economic and coupled hydro-economic models (Kuwayama and Brozović 2013; Latinopoulos and Sartzetakis 2015; Madani and Dinar 2013; Mulligan et al. 2014). While these models may include multiple behavioral characteristics of human actors, they usually assume effective enforcement of the instruments. Other, more empirically-based research has been carried out to study the practical implementation of such instruments in different societal contexts (Mukherji and Shah 2005; Ross and Martinez-Santos 2010; Wester et al. 2009). This GRIPP Case Profile contributes to the literature on the practical implementation of groundwater abstraction regulations using smart card machines (Box 1) by documenting two cases from North China.

Smart card machines have been introduced across at least six provinces in North China since the early 2000s under different local conditions to support groundwater demand management objectives (Wang et al. 2017). The use and implementation of the smart card machines remain uneven across the region. Currently, the semi-arid and arid provinces in the northwest, such as Gansu and Xinjiang, are ahead in the use of the machines, even though its use first developed in the northeast provinces. Yet, adoption of the machines in the northeast provinces has been limited by early technology limitations and poor system upgrades. However, the northwest provinces have benefited from lessons learned in the early stages.

Box 1. Smart card machines for groundwater control: How does it work?

The smart card technology for groundwater wells was developed in China in the early 2000s to control groundwater use for irrigation. The technology is suitable for use with volumetric groundwater pricing as well as quota regulation mechanisms (Liu et al. 2009) (Box 2). The steps involved in the application of the technology include the following:

- A smart card machine and water meter are installed on the pumping installation. The pumping installation consists of a well and a pump connected to the electricity grid.
- The irrigator has to swipe a magnetic card in front of the display of the card machine to turn on the pump.
- The volume of water pumped is measured by the water meter and recorded by the smart card machine and the card.
- The pump can be turned on and off manually by the irrigator as long as there is credit in the water account on the card. However, once the water account is depleted, the electricity connection is interrupted and the pump is turned off automatically.
- The pump can be turned on again after reloading the card at a station providing this service.

Smart card machine installed on pumping installation.
Photo: Eefje Aarnoudse

Box 2. Groundwater regulation mechanisms.

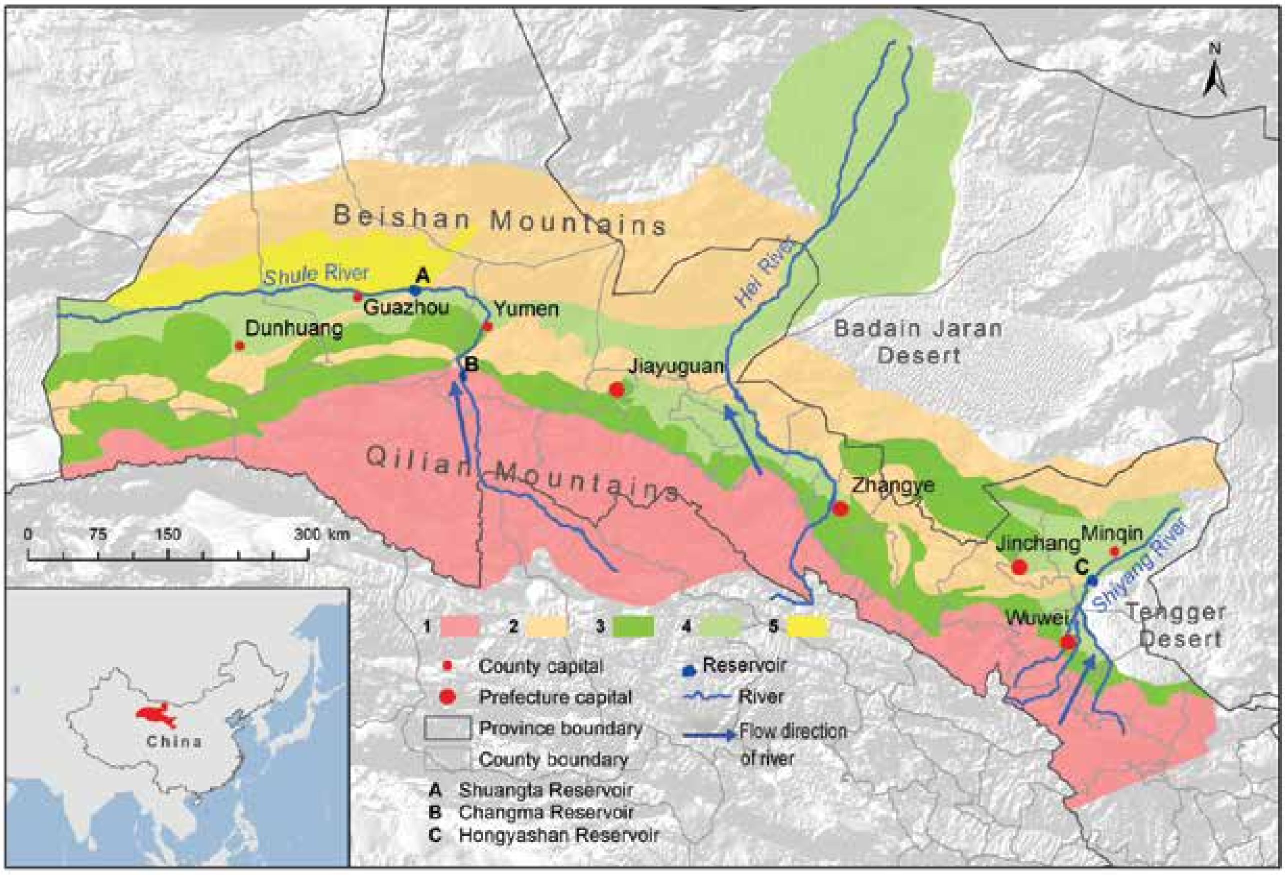
Groundwater quotas
Regulation of groundwater abstraction through water quotas implies that total water use is controlled by allocating a maximum number of water withdrawals to each user. When the quotas are set below prior water use, quota regulation can induce farmers to save water (Mohamed and Savenije 2000).

Tiered groundwater pricing
Tiered groundwater 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 and Zilberman 2014: 2). Tiered pricing (also called increasing block tariffs) is expected to stimulate users to save water, while securing a limited amount at affordable levels for all users.
Source: Aarnoudse et al. 2016.

2. Agricultural groundwater development and management in the Hexi Corridor, Gansu Province

The Hexi Corridor in Northwest China is a long passage of arable land (approximately 1,000 km X 200 km) between the Qilian Mountains in the Southwest and low-lying desert lands in the Northeast (Figure 1). The major part of the Hexi Corridor belongs to Gansu Province. The area is crossed by three inland (endorheic) river basins: the Shule, the Hei and the Shiyang river basins (Figure 1; Box 3). The cases described here involve the Guazhou and Minqin counties. Guazhou County is located at the downstream reaches of the Shule River. However, under natural conditions (i.e., without human alteration of the hydrological system), the river still continues its way to Dunhuang County (Figure 1). Minqin County is located at the tail end of the Shiyang River.

Figure 1. Map of the Hexi Corridor.



Source: Adapted from Zhou et al. 2007
Notes: 1 = High rock mountains, 2 = low rock hills, 3 = alluvial fans, 4 = alluvial plains, and 5 = foothill plains.

Box 3. Hydrogeological and climatic conditions of the Hexi Corridor.

Average annual river runoff for the three rivers ranges from 1,500 to 2,100 million cubic meters (Mm^3) per year (Gansu Province Water Resources Bureau 2008). The rivers originate from snowfall and glacial melt in the Qilian Mountains and naturally end as wetland oases in the desert. The alluvial plains in the lower parts of the basins are characterized by a semi-arid climate. Annual rainfall lies between 50-200 mm and annual evapotranspiration is between 2,000-3,500 mm. The plains are underlain by high-storage, mostly natural freshwater aquifers made up of unconsolidated sediments (cobble gravel, fine sand and clay) up to 200-300 m thick and directly connected to the rivers (Edmunds et al. 2006; Ji et al. 2006). The downstream areas are naturally characterized by shallow groundwater and springs.

Reduced surface water flow due to upstream expansion of irrigated agriculture and intensive pumping has led to falling groundwater tables in the downstream areas over the last few decades (Guo et al. 2009; Ji et al. 2006; Sun et al. 2009). Because the natural vegetation relies on high groundwater tables, a decrease in the levels can be disastrous for the tail-end wetlands and exacerbates desertification rates (Zhang et al. 2008b). Reduced recharge in downstream areas from fresh surface water through the streambeds and unlined irrigation canals, and pumping from deeper groundwater layers, has also diminished the quality of groundwater and led to soil salinization (Ji et al. 2006).

The plains of the Hexi Corridor are an important agricultural region. Until the 1990s, the area used to be Gansu Province's breadbasket, where wheat and maize were the main crops cultivated. Since then, cash crops such as melon, grapes and cotton were increasingly grown. The region is primarily characterized by smallholder irrigated agriculture with farm plot sizes typically below 1 ha. Prefecture capital cities are typically well below 1 million inhabitants and county capitals around 50,000 inhabitants. In the absence of megacities and with few extractive industries, the agriculture sector represents 80-90% of total water withdrawals. Water for domestic use in rural areas comes from reticulated communal well systems (typically 300-400 m deep). In the agricultural areas located upstream of the Shule and Shiyang rivers, surface water is primarily used for irrigation, whereas surface water and groundwater are used in conjunction in the downstream Guazhou and Minqin counties. Here, farmers usually apply surface water in the early cropping season and switch to groundwater in the late cropping season, when surface water is no longer available.

Minqin County's irrigation districts are supplied with surface water from the Hongyashan Reservoir, while Guazhou County is supplied from the Shuangta Reservoir (Figure 1). Canal irrigation systems divert water to farmers' fields and are managed by a hierarchical water administration. At river basin level, River Basin Organizations (RBOs) are responsible for water allocation between upstream and downstream irrigation systems. At irrigation system level, a county-level government agency is responsible for the distribution of water among irrigation districts. Practical managerial tasks are carried out by Irrigation District Bureaus (IDBs) residing in local towns and water user association (WUA) boards at village level. In most cases, the WUA board consists of the same members as the village committee in charge of broader village matters.

In Minqin and Guazhou counties, groundwater has essentially developed without interference from the government. In Minqin County, the groundwater boom took off in the 1970s, primarily in response to reduced surface water inflow due to expansion of surface water irrigation upstream. During those early years, investments in tube well[1] drilling were made by collective farms. At this time, farmers primarily used diesel pumps. However, after rural electrification in the 1980s, farmers switched to electricity for groundwater pumping. Over the years, the use of groundwater allowed farmers to expand the cropping area by 20% in the tail-end delta (Li et al. 2007). Land expansion usually took place informally and was not taken up in farmers' land-use rights documents. Since the 1990s, investments in well drilling were occasionally made by individual households that would cultivate the additional land. However, despite the dissolution of collective farms, most of the time farmers still invested collectively in well drilling. They divided the newly acquired land equally among the households. At its peak in the early 2000s, groundwater abstraction in Minqin County reached 600 Mm³/year from around 7,000 wells, while recharge through river inflow was reduced to only 100 Mm³/year (from 500 Mm³/year in the 1950s) (van Wonderen et al. 2008).

In Guazhou County, groundwater irrigation only developed later, in the 1990s. Here, the groundwater boom was triggered by a migration project, which resettled rural inhabitants from remote mountainous areas in the Gansu Province to the Shule River Basin (Zhang and Zhang 1996). At that time, the state provided the migrants with land and invested in wells for irrigation. Over the years, farmers in old and new settlements continued to invest in drilling their own wells. Most wells are drilled collectively by a group of farmers, as only a very small number of wells belong to individual households. All wells are connected to the electricity grid. Groundwater pumping has been used to informally expand the cropping area, and village leaders reported an average expansion of 40% over the period 2003-2013. In the Shule River Basin, around 2,300 wells are in use and annual groundwater abstraction is estimated at 180 Mm³/year, while the recharge capacity reaches only 70 Mm³/year (Shule River Basin Management Bureau 2013).

At government level, the responsibility to manage groundwater is assigned to different agencies in Minqin and Guazhou counties. In Minqin, groundwater is managed by the government agencies also responsible for managing surface water from river basin to water user level. However, in Guazhou, surface water and groundwater are managed by separate government agencies. The RBO of the Shule River Basin is responsible for surface water management and supervises lower-level agencies at irrigation system and irrigation district level. However, the government agency responsible for groundwater management at county level is part of the municipal government and not under the jurisdiction of the RBO. At field level, groundwater use is organized similarly in both counties. To access groundwater, farmers are organized in small groups of 30 to 70 households. The structure of these farm groups is based on old institutions from the period with collective farms. From the 1950s until the late 1970s and early 1980s, farming was organized in production brigades and production teams. These structures have been transformed into the villages and farm groups of today. One village is usually made up of five to 10 farm groups. The households belonging to one farm group cultivate crops on small plots scattered around the housing area and typically share ownership, and use and manage several tube wells. Whereas households make individual cropping decisions, the operation and maintenance of wells are primarily organized collectively at farm group level (Aarnoudse et al. 2012).

[1] Tube wells provide water through a perforated tube bored into the aquifer. This technology is used for all irrigation wells in Minqin and Guazhou counties.

Each well (typically 60 to 100 m deep) is equipped with a fixed pumping installation connected to the electricity grid. Electricity provision is generally affordable and reliable. Water is mostly delivered during separate irrigation turns from the pumping station to multiple plots through open-air cement and earth canals. Usually, one person is assigned the task of operating and maintaining the well. This so-called well operator is responsible for turning on the well at the start of an irrigation turn, while each farmer is personally in charge of irrigating his/her own plot. The well operator is one of the farmers from the farm group and most of the time also the farm group leader, i.e., the farm group representative in official village meetings. Farm group leaders are usually collectively appointed and the position is handed over after a couple of years.

3. Smart card machines linked to quotas and tiered pricing to remediate groundwater depletion

In both Minqin and Guazhou counties, local government agencies have assumed the responsibility for regulating groundwater abstraction, as stipulated in the 2002 revision of the Water Law of the People's Republic of China. Although this Law played an important role in the background, direct drivers of policy implementation differed between the two cases. In Minqin, earlier attempts by local authorities to relieve water stress through migration policies and regulating farmers' groundwater use bore little success (Aarnoudse et al. 2012; Bondes and Li 2013). Hence, in 2007, the central government stepped in and pushed for far-reaching policies to bring the desertification in Minqin to a halt. A comprehensive river basin management plan for the Shiyang River was adopted, which foresaw fundamental reallocation of surface water and groundwater resources within the river basin. The plan was launched with support from the central government, which provided around USD 600 million for its execution. In order to restore groundwater levels and maintain minimum environmental flows to the tail-end area, surface water inflow to Minqin was to increase from 100 Mm^3/year to more than 200 Mm^3/year, and groundwater abstraction should decrease from 600 Mm^3 to less than 200 Mm^3 (van Wonderen et al. 2008). Through a performance evaluation system, water officials at different administrative levels risk losing their jobs when the allocation targets are not met (Yu 2016). China's performance evaluation system, which allows higher-level authorities to steer promotion decisions of lower-level officials, is increasingly used for environmental policy implementation (Tsang and Kolk 2010).

In Guazhou, the central government did not directly intervene with regard to groundwater policies. Here, the implementation of new groundwater policies was shortly preceded by the establishment of an RBO for the Shule River in 2005. The RBO took over the responsibility for surface water management (but not for groundwater management) from the local municipal government. Consequently, the municipal government was also deprived of its previous income from surface water fees. Officially, the new groundwater policies were implemented to curb farmers' groundwater use, as also stated in policy documents (Government of Guazhou 2015). However, it cannot be ruled out that the transfer of surface water management responsibilities to the RBO and the subsequent loss of revenue from surface water fees also played a role in the decision of the municipal government to implement groundwater pricing, as it would generate an alternative income stream.

In order to implement the policies of groundwater use control, smart card machines were installed starting from 2007. Currently, all irrigation wells in both counties are equipped with such smart card machines and each farm group is provided with one card per well[2] (Aarnoudse et al. 2016).

In the two cases presented here, different types of regulatory mechanisms were chosen to control groundwater use with smart card machines. Minqin County opted for **non-tradable[3] groundwater quotas**, which belong to the category of command and control instruments, while a **tiered pricing system** was introduced in Guazhou, which belongs to the category of abstraction tax systems (Box 2) (Montginoul et al. 2016). According to official sources, the quota regulation in Minqin has helped to reach the reduced groundwater abstraction target (from 600 to 200 Mm^3/year) (Table 1) (Meng 2013). The quota has been implemented in combination with other policy measures, such as well closure and increased surface water supply (from 100 to 200 Mm^3/year), which partially offset the reduced groundwater abstraction. The officially announced reduction in groundwater abstraction is in accordance with farmers' own perceptions on groundwater use trends and observed changes in groundwater use practices after the implementation of the smart card machines. In Guazhou, a clear target for groundwater abstraction reduction was not set and official data on abstraction before and after the policy are lacking. Based on farmers' own perceptions on groundwater use trends and observed groundwater use practices, the tiered pricing system seems not to have resulted in a reduction in groundwater abstraction.

[2] In Minqin, it was originally conceived to provide one card per household, but one card per well turned out to be more practical under the existing collective well operation and management conditions.
[3] Although localized, informal groundwater trading has been reported elsewhere in North China (Zhang et al. 2008a), this is not commonly practiced in the study area. One reason for this could be that the share of wells owned by individual households is smaller than observed elsewhere in North China. Under the current quota regime, trading of quotas between households is not allowed.

Moreover, the authors' own survey results show that farm households in Guazhou apply more than double the number of groundwater turns per household per year compared to Minqin, despite a similar level of surface water use and household size (Table 1). In line with this, it can be observed that more water-intensive crops such as melon are grown in Guazhou instead of sunflower and fennel, which are grown more widely in Minqin. Whereas this study cannot quantify the factors that determine the variation in groundwater use between households in the two counties, these figures indicate that, at farm household level, groundwater use in Guazhou is less restricted than in Minqin.

Table 1. Land and water use characteristics of Minqin and Guazhou counties.

	Minqin County	**Guazhou County**
Groundwater regulation mechanism	Quota	Tiered pricing
Total area	16,000 km²	23,000 km²
Population	290,000	150,000
Cultivated area (2010) - *Before policy reforms (2005)*	42,000 ha* *60,000 ha*	38,000 ha -
Groundwater recharge from surface water supply (2010) - *Before policy reforms (2005)*	200 Mm³/year* *100 Mm³/year*	70 Mm³/year** -
Groundwater abstraction (2010) - *Before policy reforms (2005)*	200 Mm³/year* *600 Mm³/year*	180 Mm³/year** -
Number of groundwater wells (2010) - *Before policy reforms (2005)*	4,000* *7,000*	2,300** -
Major crops*** (percentage of land covered)	Cotton (32%), sunflower (22%), maize (17%), fennel (12%)	Cotton (60%), melon (37%)
Cultivated land per household***	0.89 ha	2.2 ha
Number of household members***	4.6	4.1
Gross crop revenue***	CNY 28,000/ha (USD 4,480/ha)	CNY 35,000/ha (USD 5,600/ha)
Groundwater use*** (number of irrigation turns per household per year)	2.2	5.0
Surface water use*** (number of irrigation turns per household per year)	2.2	1.9

Sources: Gansu Province Water Resources Bureau 2007; Shule River Basin Management Bureau 2013; van Wonderen et al. 2008; and authors' own survey.

Notes:
* These are the targeted figures in the Shiyang River Basin Management Plan. According to official sources, these targets have been met (Meng 2013).
** These figures are for the Shule River Basin. Within the river basin, groundwater use primarily takes place in Guazhou County.
*** Based on own household survey, including 105 households in Minqin and 44 households in Guazhou, conducted in the study area in 2013 and 2014 (for more information on the data collection, see Aarnoudse et al. [2016]).

3.1. Groundwater quotas in Minqin County

3.1.1 Policy implementation

Two important measures were taken to increase the surface water inflow to Minqin. First, the irrigation districts in the upstream part of the basin had to reduce its surface water abstraction by about 10% (Gansu Province Water Resources Bureau 2007). This was largely achieved by improved water-use efficiency through canal lining. Second, additional surface water supply from the Yellow River Basin was transferred to Minqin from 2001 onwards. The volume of water transferred increased from 40 Mm^3/year in 2001 to 90 Mm^3/year in 2012 (Gansu Province Water Resources Bureau 2012).

To reduce groundwater pumping, the local water administration closed down 3,000 out of 7,000 wells from 2007 to 2010. The policy was locally known under the slogan "close the wells, reduce the farmland." Most of the wells selected for closure were located at the edge of the desert. The surrounding land was abandoned after closure. At village level, the WUA board was in charge of selecting appropriate wells for closure. The role of WUA boards as middlemen between the authorities and common farmers facilitated the implementation of the well-closing policy (Aarnoudse et al. 2012). Besides closure, a well drilling permit system was implemented, which strictly banned the drilling of new wells. Currently, well drilling permits are only released to replace dysfunctional wells.

After well closure, the remaining 4,000 wells were equipped with smart card machines in order to enforce a per capita water quota for all farm households. Since 2010, farmers' groundwater pumping is restricted based on the distribution of annual water quotas. The per capita water use quota is set at 1,200 m^3/year, which corresponds to an irrigated area of 2.5 mu (0.17 ha) per person. Previously, the average irrigated area in Minqin was estimated at 5.0 mu (0.33 ha) per person. This exceeded the official land-use rights due to land clearing at the edge of the desert over the last few decades. Hence, in an indirect way, the new policy was a way to enforce the formally allocated land-use rights. The water volume was calculated based on irrigation requirements of relatively low water-intensive, drought-resistant crops typically grown in the region under flood irrigation. The quota consists of a surface water share and a groundwater share. The size of the groundwater share is flexible and depends on annual surface water availability. As such, the buffer function of conjunctive surface water and groundwater use is taken into account. This implies that the aquifer system is considered as a reservoir where water can be stored and from which it can be extracted, depending on the inter-annual availability of surface water. In this context, flexible groundwater use can reduce the risk associated with surface water availability constraints during droughts (WRDMAP 2010).

In general, surface water supply to farmers in Minqin has improved due to the surface water management interventions upstream and the inter-basin water transfer. Farmers reported to have received two to three surface water irrigation turns in 2012, compared to zero to one turns a decade before. However, annual variability in snowfall remains a natural factor, which influences the surface water inflow. In essence, surface water irrigation is prioritized, and farmers' groundwater use is restricted. Farmers are only allowed to pump groundwater up to the share allocated by the combined quota, which cannot be supplied with surface water. At the beginning of the cropping season, the available surface water volume is estimated based on the water level in the Hongyashan Reservoir. The combined quota and annual adjustment mechanism is overseen by the local IDB throughout the cropping season. Farm groups need to reload their cards at the beginning of each irrigation turn, so that the irrigation interval and volume can be adjusted by the IDB's office. When a farm group has just received an extra surface water turn, they will have to skip the next groundwater turn. Although farmers' groundwater use is restricted, they are still assured of a fixed, and known, reliable amount of water on which to plan their cultivation.

3.1.2 Impacts and limitations

Groundwater pumping data recorded by the smart card machines are not made public. Therefore, it is hard to verify whether the water volumes used by farmers actually correspond to the quota allocated on paper. Survey respondents have confirmed, however, that the smart card machines are actually installed and functioning well on all pumping installations. Moreover, it can be observed that the new policy has strongly altered the operation of groundwater wells. Farmers can no longer decide independently when to turn their groundwater pumps on and off. All in all, 80% of the households reported that their groundwater use per unit of land has reduced over the years 2002-2012, i.e., after implementation of the new groundwater policies. On average, farmers applied 2.2 groundwater turns and 2.2 surface water turns during the cropping season just prior to the survey (Table 1), whereas they would irrigate only once with surface water, while up to six times (for wheat) or even eight times (for melon and maize) with groundwater prior to the new policies.

Because farmers' livelihoods strongly depend on irrigated agriculture, groundwater use restrictions have had an important impact on farmers' major source of income (Li et al. 2014). Based on a large survey of 300 farm households in Minqin, around 65% of the farmers reported a reduction in income since the implementation of the policies (Huang et al. 2017). Moreover, Fan et al. (2014) identified that farmers' present net income in Minqin is too low to invest in and adopt new farming techniques, such as water-saving technologies, which could potentially increase their revenue under restricted water-use conditions. Farmers' cultivation practices have changed in two major ways. First, farmers have abandoned previously cultivated land. Village heads surveyed reported a decrease in cropping area between 8 and 23% over the period 2002-2012. Second, farmers made a shift to low water-intensive crops. For example, one interviewee explained that she used to intercrop maize and wheat, but groundwater use restrictions prevented her from growing both crops during one season. The most obvious crop change is the rapid shift away from melon production. However, none of the farmers were forced to give up farming, as each household is secured a minimum amount of water (and implicitly, land). Also, due to the collective use of several wells by each farm group, well closure and consequent land abandonment implied that each farmer lost only a share of his/her land.

Whereas the agriculture sector has encountered water and economic losses over the last decade as a result of the comprehensive 2007 river basin management plan, a positive impact on groundwater levels and the natural environment has been observed (Hao et al. 2017; Xue et al. 2015). Moreover, the wetland oasis at the tail end of the river basin was partially regenerated. The tail-end lakes, which had disappeared in the 1950s after early surface water irrigation development, reappeared in 2011. Although the restored lake area covers only a fraction of its original size, neighboring farmers reported that the local climate had improved since the lake returned, with an increase in rainfall and fewer sandstorms than before.

Despite the success in terms of environmental restoration, restriction policies are not popular amongst the local population. However, because the policies are backed and enforced by the central government, farmers are in a rather powerless position. Protests in rural China are most likely to be successful when citizens gain national attention and find the central government on their side (for example, in the case of food and water pollution scandals) (Gilbert 2012). In Minqin, sparse counteractions have occurred to oppose the groundwater regulations, e.g., by breaking smart card machines or paying kickbacks to receive more water (Aarnoudse et al. 2012). However, one of the water officials interviewed explained that, even though illegal pumping is detected every now and then, violators can expect high fines. Many farmers submit to the new policies. Moreover, local officials are under strong pressure to reach the groundwater abstraction targets. Thus, instances of noncompliance may occur, but it does not undermine policy implementation as typically found elsewhere (Scott and Shah 2004). Due to environmental restoration, there is also a certain level of acceptance amongst the population, particularly in the villages neighboring the desert where the threat of desertification is highest. The vast majority of farmers surveyed agreed that uncontrolled groundwater pumping has negative consequences.

In order to compensate for farmers' income losses, rural development support projects ran in parallel to the groundwater use restrictions. They included numerous water-saving and income-generating initiatives promoting different measures such as greenhouse crop production, drip irrigation and the cultivation of low water-intensive crops. A major project foreseen in the river basin management plan was the construction of greenhouses on 2,500 ha of land (Gansu Province Water Resources Bureau 2007). Through the use of drip irrigation and the production of high-value crops, greenhouses would allow farmers to increase their water productivity and incomes despite groundwater use restrictions. In addition, there was a plan to install 1,200 ha of drip irrigation for outdoor cropping. However, both the introduction of greenhouses and drip irrigation faced much resistance from farmers, because they considered the cultivation methods unsuitable under local conditions. Many greenhouses have been left unused after construction. Drip irrigation has been rejected particularly in the tail-end region, where farmers consider groundwater too saline to be dripped in small concentrations at the root zone. In response, the water authorities are currently building small surface water basins to allow for pressurized drip irrigation with surface water. In 2010, the county government started a new initiative to secure farmers' incomes under the slogan "Special Fruit Tree Industry." This project promoted, in particular, the production of relatively low water-intensive crops, such as grape, goji berry and date, on 2,000 ha as part of new crop value chains developed in Minqin (Long and Lin 2011). Farmers' views on the project are mixed. Some are willing to try new crops and happy to receive support, whereas others (particularly elderly farmers) feel forced to grow unknown, labor-intensive crops.

3.1.3 Future development trends

As envisaged in the original river basin management plan, the rivers' tail end has recovered as a natural wetland and irrigated agricultural land has diminished over the years. However, what will happen to upstream townships of Minqin is unclear. Giordano (2009) forecasted that the problem of intensive groundwater use in China will be resolved naturally as more and more rural (mostly young) inhabitants give up farming and leave the countryside for an urban living. Yet, considering current trends of economic development and associated changing food demands, this is unlikely to happen. New constellations of farm holdings appear as soon as elderly farmers give up crop cultivation. In some villages in the Hexi Corridor, farming is taken over by large agri-businesses which informally rent land from small land-use rights holders. Moreover, often, a few households take over the land, while others leave the village. It can be expected that ongoing water restrictions will be an additional reason for farmers to move out of agriculture, and land consolidation will continue to take place in one way or another. The question is whether this will reduce the region's water stress with the use of modern water-saving technologies and increased water-use efficiency; or whether long-term environmental targets will be disregarded as large landholdings have more power to fight for unrestricted access to water than small landholdings.

3.2 Tiered groundwater pricing in Guazhou County

3.2.1 Policy implementation

Until 2007, no volumetric groundwater fee had been paid by farmers in Guazhou County. In 2007, the municipal government installed smart card machines on all groundwater wells, along with the implementation of a tiered groundwater pricing system and a control on the drilling of additional wells through a newly enforced permit system. The municipal government charged the groundwater fee on top of the existing electricity fee paid by farmers for pumping. The volumetric groundwater price was set at CNY 0.01/m³ (USD 0.0016) for the first consumption block of 100,000 m³/per well, and CNY 0.02/m³ (USD 0.0032) for consumption beyond that block within a given year. Generally, farmers do not pump more than 200,000 m³ per well per year (Aarnoudse et al. 2016).

Village leaders and well operators are well aware that different prices are paid for different consumption blocks. However, the pricing threshold is not known to ordinary farmers. Within each farm group, total costs of individual households are recovered through a combined rate calculated either per hour or kilowatt hour (kWh), which includes the groundwater abstraction fee, electricity fee, and the operation and maintenance costs. The combined rate is fixed based on a cost estimate, so that the price difference for water pumped beyond 100,000 m³ per well is not passed on to the individual households, even though actual groundwater use decisions on abstraction take place at this level. The irrigation interval is usually decided collectively by the farm group, i.e., when to start a new irrigation turn. However, individual households can decide how much water to use per turn and/or skip turns for specific plots. Moreover, the groundwater fee is usually paid once by the farm group as a deposit based on an estimated amount of water required at the beginning of a cropping season. In practice, this is also the only time that the smart card is reloaded at the municipal government (unless more water is required than estimated). This means that farmers can continue to use the pumps without interference throughout the season. Hence, a control mechanism on the irrigation interval and volume, as is the case in Minqin, is absent in Guazhou.

3.2.2 Impact and limitations

Although the new groundwater pricing policies have been enforced effectively (the machines are installed and groundwater fees are being paid), farmers' did not report a declining groundwater use trend over the years 2003-2013. Forty-percent (40%) of the households surveyed reported that their groundwater use per unit of land had not changed over these 10 years, while another 40% even stated that their use had increased. Moreover, in general, the farmers surveyed do not consider the groundwater price to be prohibitive. Contrary to Minqin County, village heads reported a steep increase in melon production over the last decade, which is usually supplied with at least six groundwater irrigation turns. Overall, farmers' groundwater use and gross crop revenue per unit of land are significantly higher in Guazhou than in Minqin (Table 1). In line with this, Guazhou has been confronted with falling groundwater tables of 0.34 m per year from 1999 to 2013 (Liu and Feng 2015).

At present, farmers only spend a small fraction of their crop revenue (approximately 5%) on groundwater pumping. Yet, in the face of abundant land resources and limited alternative water resources, the marginal value of each drop of groundwater is high. Therefore, it is questionable whether simply increasing the groundwater fee would lead to better results. A study of farmers' water demand elasticity in the neighboring Hei River Basin showed that higher irrigation water prices were likely to reduce farmers' income, without changing their water use behavior (Zhou et al. 2015). It is only when the water fee reaches the marginal value of water for crop production that responsive behavior can be expected (Huang et al. 2010). Yet, pushing up the price too much may not be politically feasible.

3.2.3 Future development trends

Currently, the agriculture sector in Guazhou County is flourishing. This means that it is relatively attractive for young generations to continue farming as long as groundwater access is not severely restricted. Although the average age of household heads in Guazhou was not significantly different from Minqin, it was striking that almost 10% of the farmers in Guazhou were in their twenties, an age group which was completely absent in Minqin. Farmers in Guazhou may, however, be confronted with growing water stress in the near future. Not only will continuous pumping further deplete groundwater resources, but surface water inflow is also expected to decrease. On average, 30% of the river flow depends on melting glaciers, which are rapidly disappearing as a consequence of global warming (Liu and Feng 2015; Piao et al. 2010). Furthermore, in 2014, the central government decided on a surface water transfer from the counties located upstream in the Shule River Basin to Dunhuang County, which is located downstream (Figure 1). This decision would lead to a reduction in surface water allocation to Guazhou.

With reduced surface water flow, associated decline in recharge from rivers and limited restrictions on intensive groundwater pumping, groundwater tables are likely to drop further. This will potentially aggravate deterioration of groundwater quality and eventually compromise agricultural production. Because the smart card machines are already in place and farmers are accustomed to the local government's interference in groundwater irrigation, it may be a relatively small step to implement other regulatory mechanisms, such as quotas, in the future. The question is whether local authorities will have the incentives to do so, as long as groundwater and surface water responsibilities are split over two different agencies and no additional pressure is exercised by the central government.

4. Summary – the regulatory mechanism behind smart card machines

Smart card machines are a useful technology to monitor farmers' groundwater use. To what extent they also allow for groundwater abstraction regulation depends on the sociopolitical context and regulatory mechanism associated with the machines. As exemplified by the two cases presented, the local, sociopolitical context has important implications on the choice of regulatory mechanism and the way they are implemented. In the first case of Minqin County, local water authorities were under strong top-down pressure to reach a given target of reduced groundwater abstraction. In this context, groundwater quotas were implemented with the use of smart card machines and integrated with additional measures, such as closure of wells and an increase in surface water supply. In the second case of Guazhou County, local water authorities were not confronted with clear groundwater abstraction targets, and incentives existed to generate revenue through the collection of groundwater fees. In the first case, farmers' abstraction of groundwater has decreased since the installation of the smart card machines. In the second case, the smart card machines do not have such a direct impact on farmers' groundwater use practices. Although farmers pay a higher groundwater fee than before, the fee has not been raised to a level that instils behavioral change. Moreover, the increasing block tariff introduced by the government is not transferred to the individual user, but evened out at farm group level and is thus not creating incentives for the individual to save money through the feedback of lowered cost from reduction in pumping.

The present study cannot draw hard conclusions on the effect of groundwater quotas and pricing mechanisms on farmers' abstraction per se, and comparison across sites with unequal conditions may be difficult. Yet, it does provide an indication that, in the broader societal context of North China, the practicability of quotas to reduce farmers' groundwater abstraction is higher than that of tiered pricing. Similarly, Molle (2009) argued that, in a case of severe water scarcity, water authorities tend to fall back on quotas rather than volumetric pricing as a policy measure to restrict agricultural water use. This is because quotas can be more readily adjusted to seasonal variability in water availability and ensure it is in line with the principles of equity. Based on the two cases presented here, this argument also seems to hold true for North China. In Minqin County, where local authorities were under high pressure to reach a strictly defined groundwater abstraction reduction target, quotas were deemed to be the most appropriate regulation measure. In Guazhou, where groundwater management is not directly influenced by the central government authorities, local authorities chose not to put a hard cap on farmers' groundwater abstraction but to introduce a tiered pricing system.

Besides the strong pressure and financial support from the central government, several other contextual conditions have been critical for the successful implementation of groundwater quotas in Minqin:

- Farmers are organized in small farm groups to abstract groundwater, which keeps the actual number of stakeholders that the authorities needed to reach out to manageable (Aarnoudse et al. 2012).
- The problem of depletion was clearly visible to groundwater users in the form of dying vegetation and encroaching desert sands. This has reduced the resistance of local inhabitants towards the policy.
- Groundwater pumping in Minqin depends completely on the grid-based electricity supply. This enabled the use of smart card machines to monitor and regulate all groundwater pumping.
- A large number of groundwater wells were closed prior to implementation of the quota. This homogenized the well density across Minqin and facilitated the implementation of an equal per capita groundwater quota for all rural inhabitants.
- Groundwater is used and managed conjunctively with surface water. This allowed existing (surface) water management organizations (such as IDBs and WUAs) to take upon them coordinated administrative tasks related to the quota.
- Groundwater and surface water reallocation policies have been integrated. Whereas farmers' groundwater use was restricted, the improved surface water supply partly offset the losses. Also, farmers are assured of a known minimum amount of water, either from groundwater or surface water, which is announced prior to the growing season.

5. Policy directions and out-scaling potential

Lopez-Gunn et al. (2011: 103) critically raised the question whether "a ruthless push toward wetland restoration is the most sensible solution when farmer livelihoods rely heavily on groundwater resources." In the case of Minqin County, the Chinese government has tried to strike a balance by assuring a minimum allowable amount of irrigation water for each rural inhabitant. Nevertheless, current groundwater regulation policies directly touched on farmers' most important source of income. Farmers' cropping area and crop choice changed since the implementation of the policy, which affected their income from agricultural production. Even when there is still potential to increase water productivity or to save water, this would imply additional investments in advanced water-saving technologies or new crops. A pertinent question is - whether it is possible at all to curb farmers' groundwater use without affecting their income, particularly in smallholder settings where farmers' investment potential is limited. In this light, an important argument in favor of quotas (instead of pricing) is that they do not bear an additional financial burden for farmers on top of the anticipated loss of income from irrigated agriculture. Another potential solution is to compensate farmers for groundwater fees through area-based subsidies, although this may be a time-consuming solution for local authorities (Wang et al. 2016a). However, in order to fully evaluate adequate policy measures in this regard, the extent of the economic impact on farm households should be assessed more carefully with before-and-after data of future regulatory interventions.

To further minimize the impact of reduced groundwater access on farmer livelihoods, the following two principles integrated in the Minqin case need to be considered in groundwater policy design and possible out-scaling of quota regulation through smart card machines:

Ensure equitable water access to all farmers. In Minqin, the groundwater quotas were set by the water authorities. In order to secure equitable groundwater access amongst the population, the quotas were calculated on a per capita basis. Each household was assigned its water-use rights based on the number of registered members. Land-use rights were distributed in the same manner after de-collectivization of the Chinese countryside in the late 1970s and redistributed based on population changes until recently. As a result, there has never been a large disparity in landholding sizes (and consequently in farm income) between households (particularly within villages). An even per capita distribution of groundwater is likely to be less applicable in other contexts with different land tenure systems. Cases from Australia show that a reduction of groundwater entitlements can also be negotiated between authorities and water users (Ross and Martinez-Santos 2010). In the Murray Darling River Basin in Australia, the level of sustainable groundwater use was assessed by the government. Yet, to incorporate the interests of water users, a differentiation was made in the distribution of entitlements between active and occasional (inactive) irrigators (Ross and Martinez-Santos 2010).

Maintain the buffer function of conjunctive use. The use of groundwater to secure access in years of low surface water flow is a valuable asset of conjunctive use in the study area. This buffering function also plays a critical role in other conjunctive use contexts found across the globe (Foster and Steenbergen 2011). An important difference between the two cases presented here is the integration of groundwater regulations with surface water management. The groundwater quotas in Minqin are adjusted to compensate for annual variability in natural surface water supply, while groundwater prices in Guazhou are fixed. In general, quotas lend themselves better for annual adjustments than pricing (Molle 2009). However, flexible conjunctive use solutions ask for good cooperation between surface water and groundwater management authorities, which is weak in most smallholder settings (Evans et al. 2014).

All in all, the case of groundwater abstraction regulation in Minqin through smart card machines is unlikely to be one-to-one replicable in other river basins and aquifers in China or elsewhere for multiple reasons. First, the water policy reforms were implemented under pervasive attention and with substantive investments from the central government. Second, Shen (2015) argued that the policy reforms implemented in Minqin are too costly to be out-scaled across China. Also, outside China, the political feasibility of such costly interventions is likely to be low. Third, important contextual conditions, which facilitated effective policy implementation, are a characteristic of China and rarely found in other countries. Nevertheless, it can be concluded that smart card machines are a useful technology to monitor and potentially also control farmers' groundwater use in a context of grid-based pumping. However, the sociopolitical context and regulatory mechanism behind the machines are critical for effective regulation, water security, and equitable distribution of benefits and burdens.

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