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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

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

41 This article presents the case of two counties located in north-west China. Economic
42 development in the region is less advanced than in China's coastal areas. Limited water
43 resources are considered to pose a major challenge to new initiatives by the Chinese
44 government to stimulate the economy in this region (Li, Qian, Howard, & Wu, 2015). In
45 both counties smart card machines for groundwater management are installed, but
46 operated in combination with different regulatory institutions. In the case of Guazhou
47 County the machines are used to implement tiered groundwater pricing. Tiered pricing
48 means that "individuals pay a low rate for an initial consumption block and a higher rate
49 as they increase use beyond that block" (Schoengold & Zilberman, 2014, p. 2). Officially
50 the tiered water pricing is expected to stimulate users to safe water, while securing a
51 limited amount of water at affordable levels for all users. In the case of Minqin County
52 the machines are used to regulate farmers' groundwater use quantity through a
53 groundwater quota system. In a quota system, total water use is controlled by allocating
54 each user a maximum allowable quantity of water withdrawal. In Minqin, a volumetric
55 groundwater pricing system has also been implemented after installation of the machines.
56 However, here the groundwater fee is based on a fixed price per volume and from the
57 outset meant for cost recovery. The two regulatory institutions implemented in Minqin
58 and Guazhou are based on different resource allocation mechanisms. The allocation of
59 groundwater quotas could be understood as a form of centralized planning, while
60 groundwater pricing intends to set economic incentives and create a market mechanism.
61 However, because the groundwater price is determined by the authorities to include a
62 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.

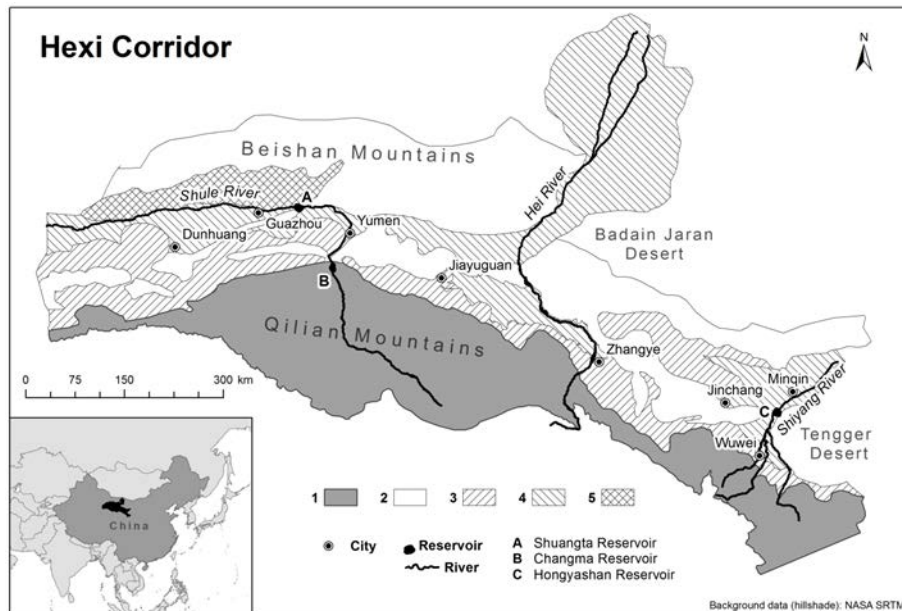
85 This article discusses the effectiveness of water quota versus tiered water pricing in a
86 setting of intensive groundwater use, based on two empirical case studies. The primary
87 focus is not on the theoretical understanding of the two regulatory institutions, but on its
88 use in a societal context. 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.

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

97 2 Research Approach

98 2.1 Case Study Area

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



110

111 **Figure 1 Map of the Hexi Corridor**
112 1= high rock mountains, 2= low rock hills, 3= alluvial fans, 4= alluvial plains, 5= foothill plains
113 Source: made by Ronald Kraemer, adapted from Zhou et al. (2007)

114

115 Minqin and Guazhou County are both located at the downstream reaches of the inland
116 rivers: Minqin in the Shiyang River Basin and Guazhou in the Shule River Basin. In these
117 areas groundwater is easily accessible, although salinity levels increase upon intensive use
118 (Wang, Ding, Shen, & Lai, 2003). Both counties contain vast areas of desert land, at least
119 90% of their total area. Annual rainfall in Minqin lies around 130 mm and evaporation at
120 2600 mm (Minqin County Government, 2015). Guazhou is even more arid, with annual
121 rainfall around 50 mm and evaporation of 3100 mm (Gansu Land Resources Bureau,
122 2015).

123 The population density in Minqin (16 inhabitants/km²) is clearly higher than in Guazhou
124 (6 inhabitants/km²). Macroeconomic conditions are fairly similar. Agriculture is the single
125 most important economic sector in both counties. The sector is characterized by small
126 scale family farming. Farmers produce a wide variety of crops; however, primarily cash
127 crops, like cotton and melon, which are sold across China. As rainfall is low and
128 evaporation is high, agriculture strongly relies on irrigation water. Due to the downstream
129 location, farmers in Minqin and Guazhou have limited access to surface water and thus
130 heavily depend on groundwater resources. In both areas groundwater use for irrigation
131 developed over the last decades of the 20th century. Though some government support
132 was available initially, eventually all groundwater wells were owned and managed by the
133 farmers themselves. Until the early 2000s groundwater use was virtually not regulated by
134 the government and intensified rapidly. At the same time shallow groundwater is the main
135 water source for the natural vegetation in both areas. Falling groundwater tables easily
136 lead to dying vegetation and increased desertification rates.

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

141 **2.2 Data Collection and Analysis**

142 This research is based on primary data collected in 2013 and 2014 in the study area. A
143 survey on surface water and groundwater use and management was carried out by a team
144 of experienced enumerators. A stratified random sample was selected to make sure
145 different irrigation districts within the counties are represented. In Minqin, 105 farm
146 households participated in the survey, spread across 10 villages in 5 different townships
147 (representing 4% of the in total 249 rural villages in the county). In Guazhou, 44 farm
148 households were interviewed, spread over 4 villages in 2 different townships (representing
149 5% of the in total 73 rural villages in the county). Respondents were asked to report their
150 water use and cropping activities for the previous cropping season and describe water use
151 and crop choice trends over the last ten years (see Appendix). In both areas the new
152 regulatory institutions started to be introduced in 2007 and had become fully effective at
153 least by 2010. By asking farmers' perception on changes over the last 10 years it was
154 possible to assess the impact of the regulation measures without making direct reference
155 to those measures and avoiding a socially desirable response. The survey also included a
156 village leader questionnaire and a well operator questionnaire in every village to collect
157 information on the (ground-) water management institutions and physical groundwater
158 use conditions at village level. In both counties, the village leaders also function as leaders
159 of the Water Users' Association (WUA). The WUA boundaries overlay the village
160 boundaries. After a preliminary analysis of the survey data, a follow-up field visit was
161 organized during which the lead author conducted in-depth interviews with water
162 managers from irrigation district to river basin level, village leaders, well operators and
163 farmers in the study area. In total 16 people were formally interviewed. The in-depth
164 interviews were used to explain irregularities in the survey data and to better understand
165 specific management institutions. Due to time constraints of the enumerator team, the
166 survey was conducted over two years. In Minqin, the survey was carried out in 2013,
167 collecting water use data for 2012. In Guazhou, the survey was carried out in 2014,
168 collecting water use data for 2013. As the time lapse consists of only one year, it is
169 assumed that changes in external factors which might influence farmers' decision making,
170 like input and output prices, are fairly negligible.

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

173 sources (i.e. answers from the village leader, well operator and household questionnaires
174 were triangulated and verified during subsequent in-depth interviews when irregularities
175 occurred). In every case the following is described in detail: 1) the underlying motivation
176 of local authorities to regulate groundwater; 2) how the respective regulatory institutions
177 have been implemented; and 3) the outcome in terms of farmers' groundwater use quantity.
178 The effectiveness of the respective regulatory institutions (i.e. whether they induced a
179 reduction in groundwater use) is evaluated in two ways. The first is by assessing
180 approximate changes in farmers' groundwater use quantity after the new regulation was
181 implemented. Because accurate panel data is missing, the assessment is based on farmers'
182 own perception of groundwater use trends over the last ten years. Second, the two
183 regulatory institutions are evaluated by comparing farmers' current groundwater use
184 quantities and related decisions (such as surface water use, crop choice and cropping area)
185 between the two cases. Though implementation might have taken place at different rates,
186 the regulatory institutions were fully implemented in both counties at the year of survey.
187 In absence of more accurate water use data, each household's average number of surface
188 water and groundwater irrigation turns is calculated per unit of land based on the survey
189 data. For example, if a farmer has one crop on 2 ha of land irrigated with 3 irrigation turns
190 ($2*3=6$) and another crop on 4 ha of land irrigated with 6 irrigation turns ($4*6=24$) the
191 average number of irrigation turns is 5 ($30/6=5$). Fan et al. (2014) also used the reported
192 number of irrigation water turns to calculate farmers' water use for different crops in
193 Minqin. It is assumed that the number of irrigation turns roughly corresponds to the
194 amount of water used per unit of land. Variation caused by the use of different irrigation
195 methods can be considered small. Basically all farmers use flood irrigation (drip irrigation
196 covers only 1% of the total irrigated area covered by the survey).

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

201 **3 Results and Discussion**

202 **3.1 Minqin County**

203 **3.1.1 Motivation for Groundwater Regulation**

204 In the 1970s and 1980s, Minqin County experienced a big tube well boom. By the end of
205 the 20th century, thousands of irrigation wells had been drilled in Minqin and annual
206 groundwater extraction was estimated to be around 600 million m³ (Gansu Province Water
207 Resources Bureau, 2007). This clearly exceeded groundwater recharge through surface
208 water inflow, which reached around 100 million m³ per year at the time (Zhang et al.,
209 2011). In 2007, the Shiyang River Basin Management Plan was officially launched. This
210 water policy reform was initiated to avoid further desertification and degradation of
211 Minqin’s environment (Wang, Zheng, & Wang, 2009). The project was financed by the
212 central government and officially kicked-off by a visit of the then Chinese Prime Minister
213 Wen Jiabao in 2007. The main target of the water re-allocation plan was to reduce
214 Minqin’s total groundwater use by almost 80% from 2005 to 2010 and more than double
215 the surface water release to Minqin from the Hongyashan Reservoir (Wonderen, Pan, &
216 Liu, 2008). The management plan is coordinated by the Shiyang River Basin Management
217 Authority. Related surface water and groundwater management responsibilities are with
218 the Water Resources Bureaus at prefecture and county level and implemented by the
219 Irrigation District Bureaus (IDB) which usually have their offices in local towns. Below
220 the province level the Chinese administration is divided into four levels: prefecture (or
221 city), county, township and village. The Water Resources Bureaus follow the
222 administrative boundaries of the prefectures and counties. The IDBs follow the boundaries
223 of the canal irrigation districts and often include more than one township. At village level,
224 the board of the Water Users’ Association (WUA) takes over surface water and
225 groundwater management tasks. Since the introduction of the Shiyang River Basin
226 Management Plan, career opportunities for water officials in Minqin are linked to reaching
227 the groundwater allocation targets. Rewarding officials for reaching environmental targets
228 is a known instrument of the Chinese national government to ensure policy
229 implementation at local level (Nickum, 2010).

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

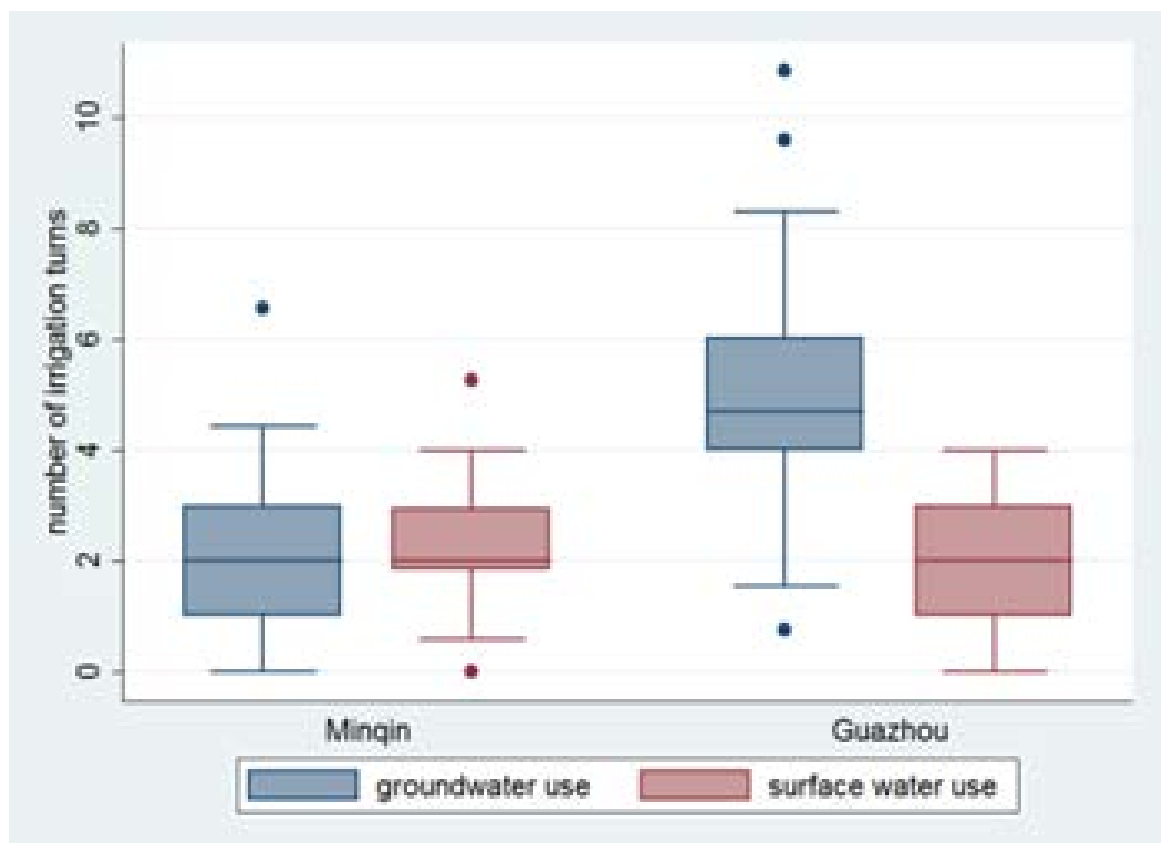
232 According to official records, 3000 out of 7000 tube wells were closed from 2007 to 2009.
233 At the same time smart card machines were installed on the remaining wells to enforce a
234 per capita groundwater quota system. The quotas were gradually implemented and became
235 officially fully effective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

238 3.1.2 Implementation of the Groundwater Quota

239 The official per capita water use quota is 1200 m³/year. (In the downstream irrigation
240 districts where evaporation rates are higher the official water quota is slightly higher.) The
241 quota is calculated based on a norm of 2.5 mu of irrigated crop land per person (1 mu is
242 0.066 ha). Before the water reforms, the per capita irrigated land was estimated to be
243 around 5 mu (Gansu Province Water Resources Bureau, 2007). According to calculations
244 by the local water authorities on crop irrigation requirements under conventional irrigation
245 techniques and local climatic conditions the quota is expected to be sufficient for low
246 water demanding, drought resistant crops, such as cotton (300 m³/mu) and sunflower (445
247 m³/mu) (Minqin Water Resources Bureau, 2009). The per capita water quota is set to
248 realize a significant reduction in farmers' groundwater use, while safeguarding basic
249 livelihood conditions for farmers. The water quota includes surface water, groundwater
250 and rainfall. Priority is given to surface water allocation, which means that the actual
251 groundwater quota can differ per year and per location depending on the surface water
252 availability and rainfall during the cropping season. Farmers pay a groundwater fee of
253 0.02 CNY/m³ to the IDB, based on their actual groundwater use. This fee is mainly meant
254 for cost recovery. Many farmers indicated that they are willing to pay a higher price for
255 more water; however, the quotas are restrictive, and selling water to fellow farmers for a
256 higher price is illegal. An electricity fee of 0.4 CNY/kWh for groundwater pumping is
257 separately paid to the electricity provider. In Minqin, groundwater use is organized at sub-
258 village level in farm groups of approximately 40 households. (Villages are usually divided
259 into smaller units. In China different names circulate referring to the sub-village units,
260 such as natural village, community, [production] team and small group [*ziran cun*, *she*,
261 *dui* and *xiao zu*, respectively]. In this article the sub-village units are consistently referred
262 to as farm groups.) In every farm group two to seven tube wells are in use. Like elsewhere
263 in China, the shared ownership and use of wells is associated with collective institutions

264 inherited from the former production teams (Bluemling, Pahl-Wostl, Yang, & Mosler,
 265 2010). Although the water quotas are officially calculated per person, the implementation
 266 is adapted to this reality. The groundwater quota is administered per farm group by the
 267 local IDB. The WUA reports the number of inhabitants per farm group to the IDB, based
 268 on which the water quota per farm group can be calculated. In order to control farmers’
 269 groundwater use during the cropping season, the groundwater is usually prepaid before an
 270 irrigation turn. A representative of the farm group needs to visit the IDB office to reload
 271 the card before each irrigation turn. This allows the IDB to adjust farmers’ groundwater
 272 quota to the annual surface water and rainfall conditions. When a farm group has just
 273 received an extra surface water turn, they may have to skip the next groundwater turn. Fair
 274 distribution of the groundwater between the households is secured through collective
 275 institutions at farm group level (Aarnoudse, Herzfeld, Bluemling, & Qu, 2015).

276



277

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

280 Household averages are based on the number of irrigation turns reported per crop and per cropping area.

281 Source: own survey

282

283

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

284

Source: own survey

285

3.1.3 Farmers' Groundwater Use

286

Typically farmers in Minqin use both surface water and groundwater to irrigate their crops.

287

Usually surface water is applied during the early cropping season and groundwater during

288

the late cropping season. During the surveyed cropping season, farmers applied on average

289

2.2 groundwater turns and 2.2 surface water turns (see Figure 2). The mean cropping area

290

per household is only 0.89 ha. The main crops are cotton, sunflower, maize and fennel

291

(see Table 1). Whether the official per capita water quotas are complied with in reality is

292

hard to evaluate based on the survey data. However, all interviewed village leaders and

293

well operators claimed that the farmers reduced their groundwater use after the smart card

294

machines have been installed. One village leader explained that they currently pump three

295

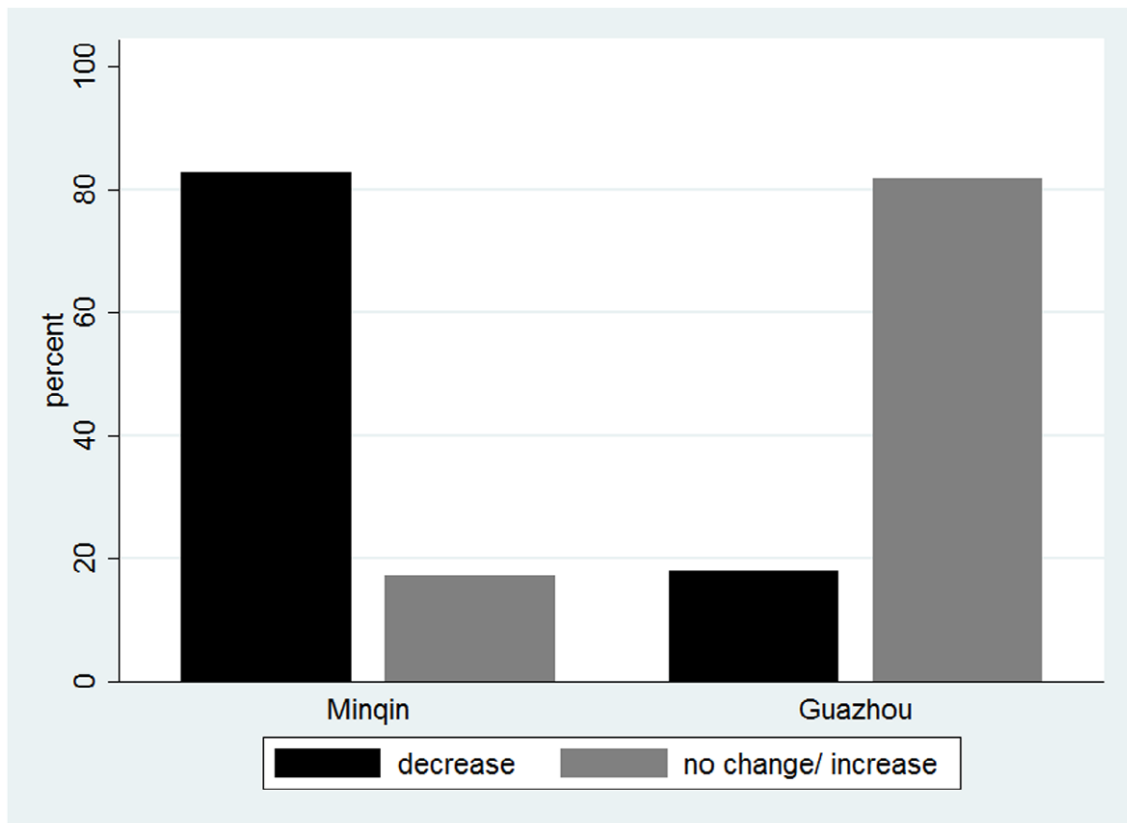
times less groundwater than they used to. Moreover, 80% of the farmers stated that their

296

groundwater use per unit of land had decreased over the last 10 years - i.e. since the

297

machines were installed (see Figure 3).



298
299
300
301
302

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

303

304 3.2 *Guazhou County*

305 3.2.1 *Motivation for Groundwater Regulation*

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

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

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

340 *3.2.2 Implementation of the Tiered Groundwater Pricing System*

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

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

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

377

378

379 **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	***

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

381 Source: Own survey

382

383 3.2.3 *Farmers' Groundwater Use*

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

395 3.3 *Comparing the two cases*

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

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

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

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

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

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

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

472 The question remains whether it is indeed the difference in regulatory institutions which
473 primarily restricts farmers' access to groundwater in Minqin compared to Guazhou.
474 Hydro-geological access conditions may also play a role. Although the natural hydro-
475 geological conditions (i.e. without human alteration) in both counties can be considered
476 similar, groundwater depth and salinity rates may differ depending on the duration and
477 intensity of overexploitation. Based on groundwater depths reported by well operators and
478 village leaders, it can be assumed that in Minqin the groundwater level is between 20 to
479 40 meters, while in Guazhou it is between 10 to 20 meters. This means that energy
480 consumption per m³ of pumped groundwater is expected to be a little higher in Minqin.
481 However, as pointed out by Hoogesteger and Wester (2015), once tube wells are in place
482 the threshold at which farmers' access to groundwater becomes critically threatened is at
483 much deeper groundwater levels (>100 m). With regard to the groundwater salinity, the
484 exact salinity rates in the two counties could not be obtained through the survey, however;
485 the groundwater salinity problem is perceived similarly in both counties. In general,
486 groundwater is considered more saline than surface water, which is the main reason for
487 farmers to prioritize surface water irrigation (when available). Moreover, in about one-
488 third of the villages in each county, well operators and village leaders assessed the
489 groundwater salinity as high (i.e. selecting 4 or 5 on a scale from 1 to 5). Thus,
490 groundwater salinity is perceived as a problem in both counties, presumably with locally
491 varying levels of severity. This means that groundwater salinity may be a reason for
492 farmers to reduce their groundwater use, but if so this would appear in both counties. All
493 in all, the most flagrant difference in farmers' access to groundwater between Minqin and
494 Guazhou is determined by the institutional conditions, as illustrated in this article.

495 **3.4 *Quota versus Tiered Pricing***

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

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

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

530 4 Conclusions

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

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

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

565

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568

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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/jqgz/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?	yes/ no
	• If yes, how did the groundwater use change? • How did the surface water use change? • What has been the reason for this change?	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 (m ³). 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?	increase / decrease / no change
	Did the surface water-groundwater use ratio for irrigation in the village change over the last ten years?	yes/no
	• If yes, what used to be the situation ten years ago? Ten years ago farmers used:	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?	yes/no
	• 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?	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). <p>How do you think farmers' groundwater use quantity has changed since the installation of the smart card machines?</p>	<p>decreased a lot / decreased a little / more or less the same / increased a little / increased a lot</p>
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