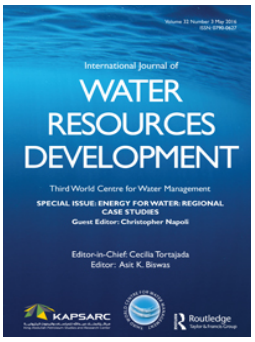

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Drivers of groundwater use and technical efficiency of groundwater, canal water, and conjunctive use in Pakistan's Indus Basin Irrigation System

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ABSTRACT
This paper explores the major determinants of heavy reliance on groundwater and the extent to which conjunctive use of ground and surface water affects the production efficiency of Pakistan's irrigators. The results show that the major drivers of groundwater use in Pakistan's agriculture are the variability and uncertainty associated with surface water delivery and that any effort to address the groundwater–energy nexus challenge should first consider fixing the problems associated with surface water supplies. The findings also suggest that having access to groundwater does not directly translate into improvements in technical efficiency of production.

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Canal irrigation; conjunctive water use; groundwater; irrigation; Pakistan; technical efficiency

Introduction

Food security in Pakistan – a country that hosts the world's sixth-largest population, more than 180 million – is intimately tied with efficient national agricultural production. Historically, agricultural production in the Indus Basin of Pakistan has relied on a vast surface network of canals that spread water from the Indus and its tributaries over large tracts of land. This system – established during British rule in India – was designed to protect against famine rather than to maximize productivity (Jurriens, Mollinga, & Wester, 1996). With growing need for increased production, surface water supplies have been increasingly augmented with pumped groundwater. The irrigation intensity in some parts of this region is now among the highest in the world, with more than 75% of agricultural land under irrigation (Siebert, Portmann, & Döll, 2010).

In addition to expansion of irrigation, fertilizer use has increased substantially and new seed varieties have been introduced to enhance agricultural productivity, improve food security and reduce rural poverty (Hussain, Mudasser, Hanjra, & Amrasinghe, 2004). These measures have led to some gains in increasing crop yields, though productivity gaps persist across the country. Punjab is the major agricultural producer among the provinces in Pakistan, with a reported share of 76% for wheat, 73% for sugar cane, and 82% for cotton in total national production (PDS, 2013). At the district (sub-provincial) scale, however, productivity varies

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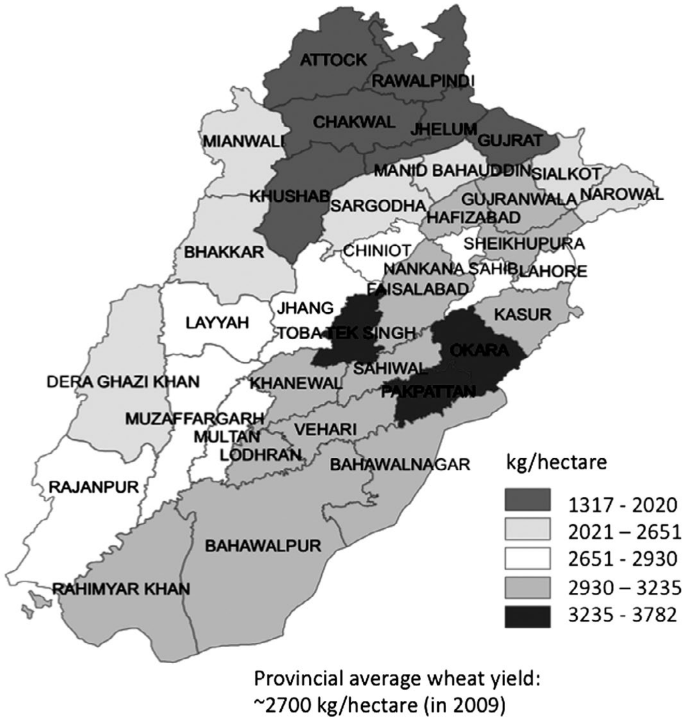

Figure 1. Wheat yield in districts of the Punjab province of Pakistan (data shown for 2008–2009). Provincial average wheat yield was approximately 2700 kg/ha in 2009. Data source: PDS (2012).

considerably (Figure 1). Yields of wheat (an important staple in the region) have increased threefold in some districts over the past three decades, whereas in other districts there has been stagnation or decline. Furthermore, the productivity gaps are also apparent in international comparisons. The maximum wheat yield in 2008–2009 was 3782 kg/ha in Pakistan's Punjab Province (PDS, 2012), compared to 4330 kg/ha in neighboring Indian Punjab (Chawla, Khepar, Sondhi, & Yadav, 2010).

Understanding the yield gap and factors affecting productivity has been an important question for socio-economic development of rural areas in Pakistan, and the country's land and water productivity has been studied in depth over the past several decades. Previous studies have estimated the productivity of irrigation water using regression analysis on farm survey data, and found that returns on irrigation water were high relative to costs of obtaining water (Hussain & Young, 1985). A micro-level analysis of groundwater markets in two districts in Pakistan indicated that all types of irrigation water – canal, purchased groundwater, and owned tubewell water – increased yields of wheat. However, groundwater had higher impact on yields than canal water, and water from tubewells owned by a farmer provided higher impact on yield (due to greater degree of control over irrigation) as compared to purchased groundwater (Meinzen-Dick, 1996). The variation in productivity across all the different canal commands has also been analyzed, and the results showed a wide range with a ratio of 1:5 in gross value of production per cubic metre of water in Punjab (Tahir & Habib, 2001). Within districts, there are further variations in productivity due to differences

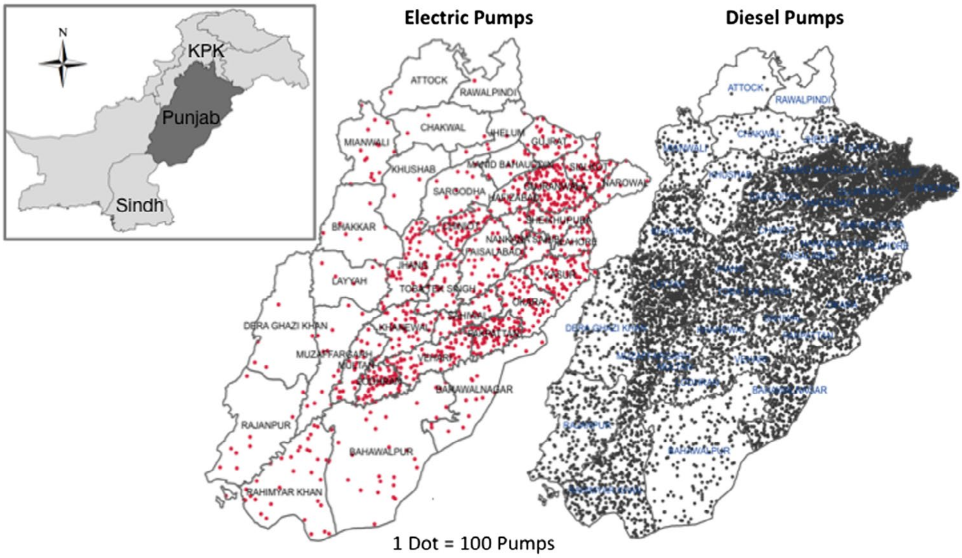

Figure 2. Electric and diesel pump installations in Punjab as of 2008–2009. Data source: PDS (2012).

in access to surface irrigation water. According to Qureshi, McCornick, Sarwar, and Sharma (2010), farms at the head of a canal receive 32% more water than farms at the tail end.

The previous work has provided important insights on the factors that have led to the emergence of a conjunctive irrigation system in Pakistan, but no work has been undertaken recently to investigate factors influencing current groundwater use. This article analyzes the current major drivers of reliance on groundwater use, followed by an investigation of the impact of conjunctive irrigation (use of both surface and groundwater) on production efficiency of wheat, using data from the Pakistan Rural Household Panel Survey conducted in 2011–2012 (International Food Policy Research Institute/Innovative Development Strategies [IFPRI/IDS], 2012). In the context of an ever-increasing reliance on groundwater use in Pakistan in the last two decades, with its consequences (increased energy demand for water extraction and application, and reduced soil health through increased salinity), this study identifies the major determinants of use of groundwater as entry points for policies aimed at addressing the groundwater–energy problem.

Literature review and background

The large-scale use of groundwater for agriculture is prevalent in many regions of the globe (Gleeson, Wada, Bierkens, & van Beek, 2012). In Pakistan, groundwater pumping started in the 1960s with a public-sector program to reduce the rising water tables in the Indus Basin due to seepage of freshwater from the canal system. In the 1970s, the government provided active support for expanding access to groundwater by paying capital installation costs and subsidizing electricity (Qureshi et al., 2010).

In the 1980s, with continued growth in pumping, the effects of over-abstraction started to become apparent. The government introduced regulations in the 1990s, including a licensing system to restrict installation of private tubewells in areas where groundwater tables were

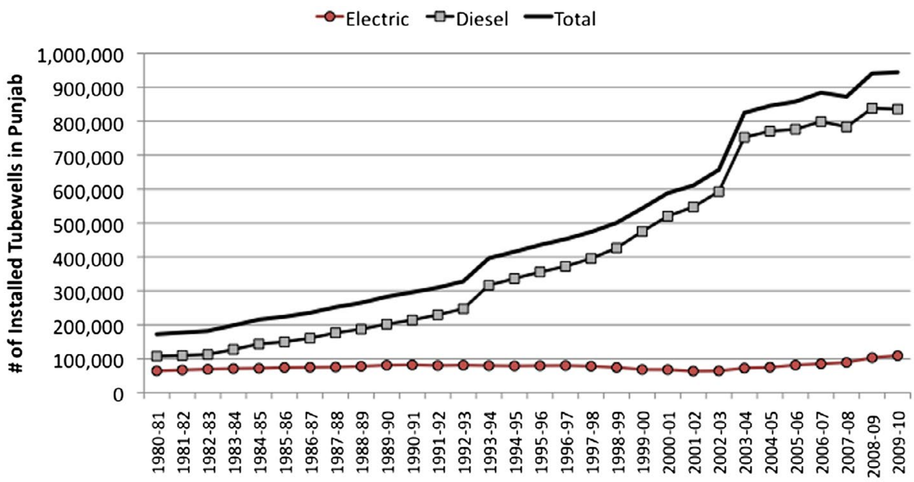

Figure 3. Total number of diesel and electric tubewells installed in Punjab. Source: MoWP (2012).

rapidly falling, and at the provincial level worked with the World Bank to prepare a groundwater regulatory framework for Punjab, the largest agricultural province in the country. In addition to direct management (through licensing), indirect approaches of energy pricing have also been applied, to little effect. The electricity tariff subsidy was removed in Punjab and Sindh in order to arrest the growth in groundwater pumping. The removal of electricity subsidies, together with a growing number of brownouts due to poor national energy policy, resulted in a shift to diesel pumps, which provided continuous access (no power cuts), were mobile and suitable for use in the increasingly fragmented land areas (due to shrinking farm sizes), and had lower installation costs. Electric tubewells were mostly used by large landowners, since the installation costs of obtaining a new electric connection from a main power line (including the costs of step-down transformers and cables) was prohibitive for small farmers (Qureshi, Shah, & Akhtar, 2003; Meinzen-Dick, 1996).

Currently, tubewells using diesel pumps constitute the major type of groundwater pumping in the country, accounting for 88% of total groundwater pumping in Punjab in 2011 (PDS, 2013). Diesel-based pumping puts appreciable demands on the energy sector in Pakistan – a country that is a net importer of petroleum products – with a reported average production of 64,000 barrels per day and consumption of 437,000 barrels per day in 2013 (EIA-Pak, 2015). The crude oil imports strain the national economy, and fuel shortages (including petrol and diesel) have grown (BS, 2015). Figure 2 shows the installation density of electric and diesel pumps in the various districts of Punjab Province.

A number of factors have been identified as contributing to growth in groundwater pumping. Hussain and Young (1985) report high returns from irrigation water (including from canal water and some groundwater pumping) relative to cost, explaining exploration of groundwater when canal water was insufficient. Various studies report that farmers pump groundwater because it allows for greater control and on-demand access, whereas canal water is unreliable and not available on demand (Qureshi et al., 2003; Kazmi, Ertsen, & Asi, 2012; Kumar, Scott, & Singh, 2013). The Indus Basin Irrigation System functions as a fixed surface supply–based system in which canal water is delivered at particular time intervals to farms. This time-based roster allocation system – known as *warabandi* – has been the mechanism of water distribution among farmers in the region (Briscoe & Qamar, 2006). Due to the unreliability of surface water supplies, however, farmers tend to over-irrigate when canal water becomes available, reducing crop yield and quality. Kumar and van Dam (2013) have also explained that in many developing countries, heavily subsidized and inefficient pricing of surface water, along with a close-to-zero marginal cost of electricity to pump groundwater, has created a situation where the private cost of marginal increase in the use of both water and electricity in agriculture is almost zero, reducing the incentive for farmers to invest in water-saving technologies.

Farmers have also resorted to increased groundwater use in times of drought. During 2000–2001, surface water availability was only 26% of 1996 levels (Qureshi et al., 2003). The drought continued for two years (Xie, Ringler, Zhua, & Waqas, 2013), followed by an almost 50% increase in new groundwater pump installations (Figure 3).

Another important factor has been population growth and associated land fragmentation, which has led to some farmland being cut off from direct access to canal water. Particularly smaller farmers often do not have access to canal water supplies, and use groundwater for irrigation (Qureshi et al., 2003).

In Punjab, groundwater is used on approximately 77% of irrigated areas, either alone or in conjunctive use with canal water (PDS, 2013). The pumping systems have provided critical access to irrigation water but have also increased the energy intensity of agricultural production in the region (Siddiqi & Wescoat, 2013). During 2001–2012, the price of light diesel oil increased from Rs. 16/L to Rs. 91/L (PEY, 2012). The electricity tariff for the agricultural sector also increased. For instance, the Multan Electric Power Company (serving districts with some of the highest agricultural electricity use in the province) had a fixed monthly rate of Rs. 70/KW in 2004, which increased to Rs. 120/KW in 2012. The variable rate increased from Rs. 2.75/kWh to 6.77/kWh during this period (PEPCO, 2013). Despite the rising energy costs (and therefore increased costs for pumping, which makes groundwater a very expensive source compared to almost-free canal water), groundwater abstractions continued to increase, indicating persistent challenges in the canal water delivery system.

This study investigates the factors driving growth in tubewell installations, as well as the impact of relying on canal water, groundwater and conjunctive use of canal and ground water as sources for irrigation, on technical efficiency of wheat production. The results inform irrigation management in this and other large conjunctive-use systems. Furthermore, they help identify entry points for energy policy reform in irrigated agriculture and policies to improve production efficiencies.

Empirical model

The empirical investigation first explores the major drivers of reliance on groundwater use, followed by an investigation of the implications of excessive reliance on groundwater vis-à-vis conjunctive use of ground and surface water on production efficiency. The next two sections explain the specific models used in the empirical approach to answer these two sets of questions.

Drivers of groundwater use

Farmers use groundwater either as an exclusive source of irrigation or as a supplement to canal water because of water shortages in the canal system at the time farmers need to irrigate their fields. But such reasoning does not directly lend itself to specific policy recommendations on how to solve shortages of both canal and groundwater. This article formally shows that water shortages are the main reason forcing farmers to use groundwater, but more importantly it identifies characteristics of canal water supply that could lead to mismanagement, aggravating shortages, and hence to increasing demand for groundwater use.

Factors that determine groundwater use can be (1) farm-specific, such as the location of the farm on a watercourse, salinity levels, waterlogging, slope, and fertility of the plots; (2) watercourse-specific, such as the location of the watercourse on the distributary, whether the watercourse is lined, whether the watercourse has a water users' association (WUA), number of farmers on the watercourse, number of tenants on the watercourse and its ratio to land owners, participation of some landlords of the watercourse in the irrigation department or other government offices, whether farmers exchange canal turns on the watercourse, land-holding distribution in the watercourse, etc.; (3) distributary-specific, such as the number of weeks the distributary or minor is open during the season, number of weeks the canal is full or half-full in the weeks the canal is officially open for the season, and whether the canal has a farmer organization (FO) that reports to the irrigation department; and (4) farmer-specific, such as household demographics and size of land holdings.

We model the reliance on groundwater (g_i) as an outcome of interest with a value of 1 if the farmer identified groundwater as the primary source of irrigation on the farm plot, and 0 otherwise. We also use tubewell ownership as an alternative outcome variable. We use the following logistic model, which includes factors that determine farmers' decisions to use groundwater as the primary source of irrigation water (or to own tubewells):

$$P\left(g_i = 1\right) = \frac{\exp(\alpha_0 + \alpha_H H + \alpha_F F + \alpha_W W + \alpha_D D)}{1 + \exp(\alpha_0 + \alpha_H H + \alpha_F F + \alpha_W W + \alpha_D D)} \tag{1}$$

where $P\left(g_i = 1\right)$ is the probability that groundwater is the main source of irrigation on the farm (or the farmer owns a tubewell); H, F, W and D are vectors of household, farm, watercourse and distributary characteristics as described above; and α_0, α_H , α_F, α_W, and α_D are corresponding parameters to be estimated.

Implications of groundwater, surface water, and conjunctive use on technical efficiency of production

A stochastic frontier production function is estimated for wheat production in Punjab, Sindh and Khyber Pakhtunkhwa (KPK) Provinces of Pakistan to explore the extent to which conjunctive use of surface and groundwater, or lack thereof, affects the technical efficiency of farms. We estimate the technical efficiency of irrigated agriculture in Pakistan and quantify the contribution of varying irrigation practices as well as household and plot characteristics to average production inefficiency.

Wheat was chosen for the analysis because of its dominance in the *rabi* (winter) season, accounting for more than 70% of cultivated land during this season (IFPRI/IDS, 2012). In addition, the focus on wheat (and the *rabi* season) is helpful to abstract from crop choice issues and the resulting crop-specific water requirements in the more diversified *kharif* (summer) season.

Variables that are expected to represent the production environment are modeled such that they will influence the mean technical inefficiency of farmers following the stochastic frontier model developed by Aigner et al. (1977) and extended by Battese and Coelli (1995) and Wang (2002). The basic formulation is:

$$y_i = x_i\beta + v_i - u_i \tag{2}$$

for households $i = 1, \ldots, N$, where y_i is the natural log of wheat production per unit of land for household i; x_i is a vector of the log of production inputs (fertilizer, capital, pesticide, labor, and volume of irrigation water – both surface and groundwater); v_i is a zero-mean random error, assumed to be independently and identically distributed as $N\left(0, \sigma_v^2\right)$; and u_i is a non-negative random variable associated with the technical inefficiency of production, which measures the percentage of output lost due to inefficiency and is assumed to be distributed as truncated normal $N^+\left(u, \sigma_u^2\right)$. The technical inefficiency component of the error term, u_i, is expressed as $u_i = f\left(z_i\delta\right)$, where z_i is a vector of variables thought to explain inefficiency, such as the relative reliance of the household on groundwater compared to surface water, and other controls that can affect technical efficiency. These control variables include soil fertility levels, average slope of the plot, soil types, WUAs, farms' locations on the watercourse, whether the watercourse is lined, location of the watercourses on the distributary that feeds the watercourse, number of weeks the distributary is officially open for the season, number of weeks the distributary was half or less than half full, presence of a distributary-level FO, tenancy status of the plot, problems of waterlogging and salinity, and household head's age and education; δ is a vector of associated coefficients to be estimated.

The technical efficiency score of farm i is computed as $TE = \exp(-u_i)$. The production function component, y_i, and the inefficiency effects, u_i, are estimated together in one step. The model is estimated for wheat production during the *rabi* season of 2011–2012 using the Pakistan Rural Household Panel Survey (Round 1.5), which provides detailed plot-level information with highly disaggregated data on irrigation types, methods and institutions (IFPRI/IDS, 2012).

The production function is specified as a Cobb-Douglas production function. Due to the extensive list of variables included in the model, translog specification with interaction terms of the variables was not tractable to converge. District-specific dummy variables are included in the production function component, while province-level dummy variables are included among the factors that explain inefficiency instead of the district dummies due to high collinearity of the district dummies with distributary- and watercourse-level variables. Of the 942 farm households in the survey, 561 farms were found that produced wheat in the 2011–12 *rabi* season. However, linking farmers' plots with watercourse and distributary names on which we have detailed information from a community survey was possible only for about 467 farms. We chose to use the smaller sample size to get more insights on watercourse- and distributary-level information. For this reason, the sample is not nationally representative. Nevertheless, it provides necessary insights on drivers of groundwater use and the impact of conjunctive use on production efficiency.

Results

Reliance on groundwater use is captured in two ways: whether groundwater is the primary source of irrigation water for the plot, and whether there is a tubewell on the farm land.

Table 1. Determinants of using groundwater as a primary source for irrigation in wheat production in Punjab, Sindh, and Khyber Pakhtunkhwa Provinces of Pakistan.

	(1)	(2)
Explanatory variables	OLS coefficients	Logit average marginal effects
Location on the watercourse: middle	0.261***	0.319***
	(0.060)	(0.080)
Location on the watercourse: tail	0.135**	0.209**
	(0.067)	(0.082)
Tenancy: own	0.023	0.023
	(0.045)	(0.041)
Use precision land leveling	−0.043	−0.042
	(0.072)	(0.080)
Total size of land ownership	−0.001	−0.001
	(0.004)	(0.004)
Household head attended school	−0.065*	−0.059*
	(0.037)	(0.034)
Family size	−0.002	−0.002
	(0.005)	(0.004)
Age of the household head	−0.001	−0.001
	(0.001)	(0.001)
Watercourse lined	0.001*	0.001*
	(0.001)	(0.001)
Water users' association in the watercourse	−0.196***	−0.232***
	(0.058)	(0.059)
Someone in the watercourse works for the irrigation department or is a politician	−0.185***	−0.116**
	(0.058)	(0.059)
Farmers sell canal turns on the watercourse	0.215***	0.163**
	(0.062)	(0.064)
Watercourse located at the tail of the distributary (compared to middle)	0.172***	0.221***
	(0.066)	(0.069)
Number of weeks the distributary is officially open in the season	−0.026***	−0.036***
	(0.004)	(0.007)
Number of weeks the canal was half or less than half full in the season	0.003	0.008**
	(0.004)	(0.004)
Distributary-level farmer organization	−0.284***	−0.182***
	(0.055)	(0.049)
Sindh	−0.563***	−0.470***
	(0.090)	(0.053)
KPK	−0.110*	−0.206***
	(0.063)	(0.051)
Constant	0.755***	
	(0.127)	
Observations	467	467
R^2	0.494	

Standard errors in parentheses.
***$p < .01$; **$p < .05$; *$p < .1$.

We present results from these alternative definitions of reliance on groundwater in wheat production in Punjab, Sindh, and KPK Provinces of Pakistan in Tables 1 and 2. In both cases, results from ordinary least squares (OLS) estimation and logit estimations are presented for comparison. However, the interpretation of findings focuses on the results from the preferred logit specification given the binary values of the dependent variables. The results from the logit specification refer to average marginal effects of the explanatory variables on changes in the predicted probabilities of the dependent variable. That is, at least for categorical variables, the marginal effects can readily be interpreted as the impact of changes in an explanatory variable on the probability of using groundwater as a primary source for

Table 2. Determinants of tubewell ownership in wheat production in Punjab, Sindh, and Khyber Pakhtunkhwa Provinces of Pakistan.

	(1)	(2)
Explanatory variables	OLS coefficients	Logit average marginal effects
Location on the watercourse: middle	0.129*	0.188**
	(0.068)	(0.074)
Location on the watercourse: tail	0.008	0.076
	(0.077)	(0.077)
Tenancy: own	−0.015	−0.028
	(0.052)	(0.047)
Use precision land leveling	−0.125	−0.130*
	(0.083)	(0.077)
Total size of land ownership	0.025***	0.026***
	(0.004)	(0.004)
Household head attended school	−0.014	−0.007
	(0.042)	(0.041)
Family size	0.003	0.002
	(0.005)	(0.005)
Age of the household head	−0.001	−0.000
	(0.002)	(0.002)
Watercourse lined	0.000	0.000
	(0.001)	(0.001)
Water users' association in the watercourse	−0.110*	−0.094
	(0.066)	(0.066)
Someone in the watercourse works for the irrigation department or is a politician	−0.188***	−0.177***
	(0.066)	(0.060)
Farmers sell canal turns on the watercourse	0.011	0.008
	(0.071)	(0.074)
Watercourse located at the tail of the distributary (compared to middle)	−0.023	−0.016
	(0.076)	(0.077)
Number of weeks the distributary is officially openin the season	−0.008*	−0.007*
	(0.004)	(0.004)
Number of weeks the canal was half or less than half full in the season	−0.013***	−0.012***
	(0.005)	(0.005)
Distributary-level farmer organization	0.010	0.017
	(0.063)	(0.064)
Sindh	−0.516***	−0.385***
	(0.103)	(0.036)
KPK	−0.223***	−0.180***
	(0.072)	(0.059)
Constant	0.511***	
	(0.145)	
Observations	467	467
R^2	0.250	

Standard errors in parentheses.
***$p < .01$; **$p < .05$; *$p < .1$.

irrigation or on the probability of tubewell ownership. Using the definition of groundwater as the primary source of water fits the data well, with an R^2 of 0.49 (Table 1), compared to using the definition of tubewell ownership, with an R^2 of 0.25 (Table 2).

The results in Column 2 of Table 1 indicate that the major driver of groundwater use in Pakistan is the shortage and unreliability of surface water delivery. Farms at the middle and tail of a watercourse are 32% and 21% more likely, respectively, to have groundwater as a primary source of irrigation compared to farms at the head of a watercourse. The higher probability for farms at the middle of a watercourse suggests a degree of complementarity between surface and groundwater use, possibly to dilute saline groundwater with sweet surface water. In addition to the location of the farms on a watercourse, the location of the

Table 3. Elasticities of wheat yield to changes in production inputs in the stochastic frontier production function.

Dependent variable (y): log of wheat yield (kg/acre)	
Explanatory variables (x)	Elasticity
Log of fertilizer used (kg/acre)	0.033**(0.015)
Log of machinery hours used per acre	0.007(0.007)
Log of number of sprays used per acre	0.001(0.001)
Log of labor days used (days/acre)	0.016(0.017)
Log of total water used (inches)	0.013**(0.006)
District fixed effects controlled for?	Yes
Observations	333

Standard errors in parentheses.
*$p < .10$; **$p < .05$; ***$p < .01$.

Table 4. Combination of groups used in the analysis based on source of irrigation water and location on watercourse.

	Groundwater	Canal water + groundwater	Canal water
Head	Group 1	Group 2	Group 5
Middle	Group 1	Group 4	Group 7
Tail	Group 1	Group 3	Group 6

watercourse on the distributary or minor that feeds the watercourse is an important determinant of reliance on groundwater use. Farms on watercourses at the tail of a distributary are 22% more likely to use groundwater as a primary source of irrigation compared to farms on watercourses at the middle of a distributary.[1] Similarly, an additional week the minor or distributary is officially open in the season reduces the probability of using groundwater as a primary source of irrigation by 3.6%, while an additional week the distributary is half or less than half full increases the probability of using groundwater as a primary source of irrigation by about 1%. All these results indicate that any effort to address the groundwater–energy nexus challenge should first consider the main cause of increased pumping, which is the insufficient and unreliable canal water supply.

The results in Table 1 also show that groundwater is less likely to be a primary source of irrigation on watercourses and distributaries with formally organized WUAs. Farms on watercourses with WUAs are 23% less likely to use groundwater as a primary source of water, while farms on distributaries with distributary-level FOs that report to the irrigation department are 18% less likely to use groundwater as a primary source of water for irrigation. These results suggest that WUAs and FOs could be strengthened and used as effective institutions to improve canal service delivery, and hence reduce excessive reliance on groundwater.

The results in Table 1 also provide evidence for significant differences across provinces in the use of groundwater in Pakistan. Farms in Sindh are 47% less likely to use groundwater as a primary source of irrigation, compared to farms in Punjab. Likewise, farms in KPK are 21% less likely to use groundwater as a primary source of water, compared to farms in Punjab. The difference across provinces in their reliance on groundwater as a primary source of water could be the result of differences in both groundwater potential and groundwater quality across the provinces in favor of Punjab. The total available groundwater resources of Punjab, Sindh, and KPK Provinces are estimated at 42.75 million, 18 million, and 3.11 million acre-feet, respectively (PPSGWP, 1998).[2] Similarly, groundwater quality is better in Punjab,

Table 5. Marginal effects on the average of technical inefficiency.

	Marginal effect on mean technical inefficiency, u	
Explanatory variables	Average marginal effect	Standard deviation
Source of irrigation water and location on the watercourse		
Household at the head of the watercourse using only canal water	−0.160	0.101
Conjunctive user of ground and canal water located at the head of the watercourse	−0.047	0.030
Household at the middle of the watercourse using only canal water	−0.190	0.119
Conjunctive user of ground and canal water at the middle of the watercourse	−0.103	0.065
Conjunctive user of ground and canal water at the tail of the watercourse	0.035	0.022
Household at the tail of the watercourse using only canal water	−0.250	0.157
Watercourse characteristics		
Water users' association on the watercourse	−0.068	0.043
Watercourse lined	0.002	0.001
Watercourse located at the tail of the distributary (compared to middle)	0.078	0.049
Distributary characteristics		
No. of weeks the distributary is officially open in the season	−0.010	0.006
No. of weeks the canal was half or less than half full in the season	0.003	0.002
Distributary-level farmer organization	0.154	0.097
Plot characteristics		
Flat land	−0.062	0.039
Slightly sloped land	−0.010	0.006
Very fertile	−0.067	0.042
Sandy soil	0.149	0.094
Sandy loam soil	0.159	0.100
Loam soil	0.026	0.017
Tenancy: own	0.015	0.009
Plots experience salinity	−0.021	0.013
Plots experience waterlogging	−0.097	0.061
Farmer characteristics		
Household head attended school	0.023	0.015
Log of age of household head	−0.005	0.003
Location variables		
Sindh	0.620	0.390
KPK	0.234	0.358
Observations	333	

Note: The dependent variable is technical inefficiency, so positive signs correspond to exacerbated inefficiency, and negative signs to improved technical efficiency.

compared to Sindh: a relatively smaller share of the canal command areas in Punjab (23%) have hazardous groundwater quality, while the share is 78% in Sindh (Qureshi et al., 2010).

The presence of landowners on the watercourse who work for the irrigation department or who are politicians reduces the probability of using groundwater as a primary source of water by about 11%. We argue that political connections of farm owners increase the chance of getting canal water in watercourses on their farms, reducing the relative reliance on groundwater.

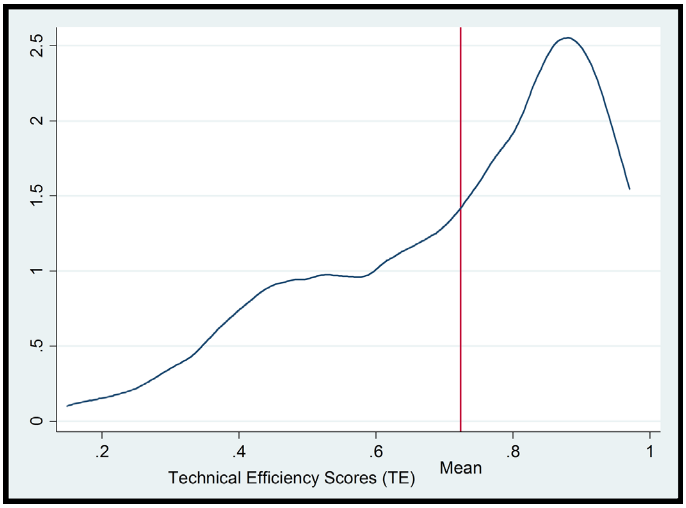

Figure 4. Kernel density of technical efficiency scores of wheat farmers in the sample. Source: authors' computation.

Watercourse lining has a positive relationship with groundwater use. Increasing canal lining of a watercourse by 10% increases the probability of using groundwater as a primary source of water by about 1%. This could be because of the difficulty of tampering with lined watercourses, forcing anyone who needs additional water to get it from groundwater. On the other hand, lined watercourses could also indicate irrigation office strategies to keep canal water separate from saline groundwater. In some places in Pakistan's irrigation system, saline groundwater is applied jointly with sweet canal water to mitigate absolute surface water shortages.

Farms with educated household heads are 6% less likely to use groundwater as a primary source of water. The survey data suggest that educated household heads have somehow managed to get more canal water from the system: they reported about 20% more frequent irrigations using canal water, reducing the need to rely on groundwater as a primary source of water (IFPRI/IDS, 2012). This does not imply that educated households are less likely to use groundwater. On the contrary, the survey data suggest that educated households use more of both canal and groundwater. However, they are less likely to use groundwater as a *primary* source of water. It is possible that better education, which is generally associated with a higher knowledge base, seems to facilitate farmers' ability to navigate the canal water delivery system to position themselves with relatively better access to canal water.

Farms on watercourses that sell canal turns to each other are 16% more likely to use groundwater as a primary source of water. Descriptive statistics show that canal water shortage seems severe in watercourses where farms sell canal turns to each other. For instance, 40% of the farmers on watercourses that do not sell canal turns report that the timing of the canal turn is as per their needs; this falls to only 11% in watercourses that sell canal turns (IFPRI/IDS, 2012). The data also show that the volume of canal water applied to wheat production in watercourses that do not sell canal turns is three times the volume of canal water in watercourses that sell canal turns. Thus, the informal canal water markets are indicators of the severe water scarcity in these specific canals, forcing farms to rely more on groundwater.

Results from using an alternative definition of reliance on groundwater in terms of tubewell ownership are presented in Table 2. Farms in the middle of a watercourse are 19% more likely to own a tubewell than farms at the head of a watercourse. The positive effect of tail-end users on tubewell ownership compared to farms at the head is not significantly different from zero. Ownership of an additional acre of land[3] increases the likelihood of tubewell ownership by 2.6%, possibly because the surface water delivery may be insufficient for large holdings, or because large farms can support the cost of tubewell installations more easily, or both. In addition, having landlords on the watercourse who work for the irrigation department or are politicians reduces the probability of tubewell ownership by 18%.

Irrigation canals and distributaries in Pakistan can be perennial (ensuring regular supply of water year-round), non-perennial (running in monsoon and summer), or inundation (running only during rainy season). The volume of these canals can also vary within a season. Thus, the number of weeks the distributary is open for the season as well as the level of the canal in the weeks it is open can influence farms' reliance on groundwater. The results show that an additional week the distributary is officially open in the season reduces the probability of tubewell ownership by about 0.7%. Likewise, an additional week the distributary is at least half full in the season reduces the probability of tubewell ownership by 1.2%. These results suggest that improving canal water delivery should be an integral part of groundwater management in Pakistan.

Farms that use precision land leveling are 13% less likely to own tubewells compared to farms that do not use land leveling. Farms in Sindh and KPK Provinces are 39% and 18% less likely, respectively, to own tubewells compared to farms in Punjab Province of Pakistan (Table 2).

The full set of estimated coefficients from the stochastic production frontier is presented in Table A1 in the online supplementary data (available at http://dx.doi.org/10.1080/07900627.2015.1133402). For ease of interpretation and analysis, the elasticities of wheat yield with respect to changes in the production inputs are presented in Table 3, while the marginal effects of the explanatory variables on average technical inefficiency scores are presented in Table 5, even though the production function and factors determining technical inefficiency are estimated together in one step as suggested in the efficiency literature. Wheat yield is found to be highly responsive to additional volume of irrigation water and to increases in fertilizer applications (Table 3). A 1% increase in the amount of irrigation water applied leads to a 1.3% increase in wheat yield. This elastic response of wheat yield to water suggests that yield from the last incremental unit of irrigation water is higher than the average yield obtained from all units of irrigation water[4]. A 1% increase in the amount of fertilizer used per acre increases wheat yield by about 3.3% (Table 3).

Technical efficiency is measured for a given level of input use; it measures how much more a farmer can produce at the same level of input use or, conversely, how much input can be reduced without reducing the current level of production. Conjunctive use of groundwater and canal water, or lack thereof, is one of the main variables affecting the technical inefficiency of farmers. It is hypothesized that this effect depends on the location of the farms on the watercourse, and hence farmers are classified into different groups based on water source and location on the watercourse. Table 4 depicts the different combinations and the groups used in the model.

As shown in Table 4, the different farmer groups are: (1) farmers who use only groundwater; (2) conjunctive users of ground and canal water at the head of a watercourse; (3)

conjunctive users of ground and canal water at the tail of a watercourse; (4) conjunctive users of ground and canal water at the middle of a watercourse; (5) farmers at the head of a watercourse using only canal water; (6) farmers at the tail of a watercourse using only canal water; and (7) farmers at the middle of a watercourse using only canal water.

The marginal effect of determinants of technical inefficiency on the average inefficiency score, computed using the method suggested by Wang (2002), are presented in Table 5. Any one of the seven groups in Table 4 could be used as comparison group; Table 5 shows the results when farms using no canal water were used as a comparison group.

Farmers who use only canal water for irrigation obtain much higher technical efficiency than those who use only groundwater, in head, middle and tail reaches of the canal (16%, 19%, and 25%, respectively). Further, the farmers who practise conjunctive use in middle reaches of the canal are 10% more efficient than those who use only groundwater (Table 5).

On the other hand, conjunctive use of ground and surface water does not necessarily lead to improvements in the efficiency of wheat production among farms at similar relative positions on the watercourse. There is no statistically significant difference in the efficiency of farms at the head of a watercourse with and without groundwater use. Similarly, there is no difference in the efficiency of wheat production for farms at the middle of a watercourse with and without groundwater. Conjunctive water users at the tail of the watercourse are even less technically efficient (by about 23 percentage points) than farms using only canal water at the tail. This is possibly due to the inferior quality of groundwater impacting production negatively in reducing yield or due to under-application of water as a result of groundwater shortages or as a result of high energy cost. A study focused on the Chaj sub-basin in Pakistani Punjab found that groundwater quality varied significantly across reaches in canal command areas and had significant adverse impacts on yields. Wheat production was highly profitable with only canal water use, and least profitable with only groundwater use (Hussain et al., 2004). Similarly, Kumar, Trivedi, and Singh (2009), who compared yield for major crops in the Bist Doab area of Indian Punjab across different sources of irrigation water, reported that wheat yield is higher (by about 10%) for canal water compared to groundwater. For at least one of the study locations, the authors argued that the better yield response of wheat to canal water could be due to better quality of the canal water in the area.

These results are also consistent with the findings of Kumar, Singh, and Sivamohan (2010) that farmers who pay higher prices for irrigation water (such as groundwater users) use it more efficiently by allocating more land and water away from wheat and rice and towards crops that give higher returns per unit of land. For instance, Kumar and van Dam (2013) showed that pomegranate grown in the north Gujarat region of India gives a net return of USD 1.8/m^3 of water, against USD 0.08/m^3 for wheat, while Kumar et. al. (2010) reported that net return for diesel pump owners in the Uttar Pradesh region of India is two to three times lower for wheat, and four to seven times lower for paddy, compared to crops such as sugar-cane, potato, pearl millet, pea, gram, mustard and linseed. As a result, and particularly when faced with growing water scarcity in semi-arid and arid regions, well irrigators are allocating more water to highly water-efficient crops (Kumar & van Dam, 2013; Kumar et al., 2010; Kumar, 2005). Thus, the lack of technical inefficiency in wheat production in our study is more likely a reflection of groundwater users' response to higher energy costs and water scarcity by directing more of their water and other inputs (including managerial oversight) away from wheat and towards other crops that provide more economic returns per unit of water or land.

It is also important to note that the virtues of groundwater over canal water in terms of control, reliability, and on-demand access, are likely to be offset by higher energy prices, due to the heavy reliance of groundwater on energy inputs, while almost all of the canal water delivery in Pakistan uses gravity irrigation. As a result, when energy prices rise, groundwater users are more likely to curtail the frequency and duration of irrigation compared to those who use canal water, with the resulting negative impact on yield and technical efficiency measures.

Given the amount of water they use, canal-only water users at the middle and tail of watercourses are 19% and 25% more efficient, respectively, than farms that use ground and surface water at the head. Similarly, canal-only water users at the tail of a watercourse are 33% more efficient than conjunctive water users in the middle of a watercourse, while conjunctive water users at the tail are 27% less efficient than conjunctive water users in the middle of a watercourse. The general trend suggests that farmers who face worse surface water shortages are more likely to use their resources as efficiently as possible, while farms with relatively easier access to water (such as those at the head or those that supplement surface water with groundwater) are found to be less technically efficient in terms of producing more for a given level of input.

The results also show that farms on sandy and sandy-loam soils are less efficient than the comparison group of farms with clay soils in wheat production. This is consistent with water leaving the root zone more quickly through sandy soils, so insufficient moisture is present. An additional week in which the distributary or minor is officially open for the season reduces technical inefficiency (and hence increases production) by 1%. Farms in Sindh and KPK Provinces are 62% and 23% less efficient, respectively, than farms in Punjab. However, farms on distributaries or minors with distributary-level FOs are less efficient than farms on distributaries without such institutions. In addition, farms on lined watercourses are associated with lower technical efficiencies, though the difference is small.

The results of the stochastic frontier model show that the average technical efficiency score for wheat production in Pakistan is 72% (Figure 4). Thus, there is a potential to increase wheat yield by about 39% (28/72) through improved management of existing levels of input use. This average technical efficiency score is comparable with efficiency scores reported by other researchers for wheat production in Pakistan. Battese, Malik, and Gill (1996) reported efficiency scores in four districts of Punjab ranging from 57% to 79%, while Ahmad, Chaudhry, and Iqbal (2002) reported a technical efficiency score of 68% among sampled farmers in Punjab, Sindh, and KPK.

Findings and conclusions

Pakistan witnessed a gradual increase in the use of groundwater resources starting in the 1960s and 1970s, when the government actively supported large-scale use of groundwater to reduce the rising water tables in the Indus Basin due to seepage from the canal system. However, since the mid-1990s, farmer-owned tubewells and pumps have proliferated at an exponential rate in the country, and this growth has led to problems of overdraft, falling water tables, and degradation of groundwater quality (Qureshi et al., 2010). In the context of continued large groundwater abstraction, this study used household survey data to analyze the major determinants of groundwater use, and the implication of groundwater use for farms' technical efficiency of wheat production.

The findings suggest that the major drivers of groundwater use in Pakistan's agriculture are the variability and uncertainty associated with surface water delivery. Groundwater is more likely to be the primary source of irrigation water for farms at the middle or tail of watercourses, and farms on watercourses at the tail of distributaries, on distributaries that are officially open for relatively fewer weeks, and on those distributaries for which the volume of water is half or less than half full for a considerable number of weeks in a season. All these results indicate that any effort to address the groundwater–energy problem should first consider the main cause of increased pumping, which is the insufficient and unreliable canal water supply.

The results also show that groundwater is less likely to be a primary source of irrigation on watercourses and distributaries with formally organized WUAs and FOs at watercourse and distributary or minor levels. These results suggest that WUAs and FOs could be strengthened and used as effective institutions to improve canal service delivery and reduce excessive reliance on groundwater.

The findings also suggest that complete reliance on groundwater significantly reduces the technical efficiency of wheat production in Pakistan. Moreover, conjunctive use of ground and surface water does not necessarily lead to improvements in the efficiency of wheat production. For a given location of farms along a watercourse, either there is no statistically significant difference in the technical efficiency of farms with and without conjunctive groundwater use, or when there is a difference, such as at the tail of watercourses, it is in favor of farms that rely only on canal water. These results are likely due to (1) inferior quality of groundwater impacting productivity negatively, (2) under-application of water as a result of groundwater shortages or as a result of high energy costs, and (3) the relatively higher cost of inefficiency on farms that face higher surface water shortages (such as those at the tail of watercourses), putting pressure on them to use their resources as efficiently as possible compared to farms with relatively easier access to water.

Overall, the results show that any effort to address the problems of groundwater abstraction and associated energy consumption should focus on the main driver of increased pumping, which is unreliable canal water supply. Fixing the problems of the canal system, be it by reducing conveyance losses in the primary, secondary and tertiary canals; by improving the governance of the canal system, such as reflected in the substantial efficiency improvements brought about by the watercourse-level WUAs; or by increasing reservoir storage capacity to reduce the uncertainties in the supply of surface water, could play an important role in reducing groundwater pumping. Improved canal water management, despite its role in reducing reliance on groundwater pumping, may not translate into improved groundwater balances, because watercourse lining or improved application efficiency will reduce return flows from the canal system. The reality of increasing energy costs of groundwater pumping, however, requires that better canal management be an integral component of the policy mix in addressing the groundwater–energy challenge.

In summary, this empirical analysis has identified important factors that influence the groundwater economy of Pakistan, and sets the stage for further work. In future work, more research is needed to investigate why access to groundwater does not readily translate into productivity and efficiency improvements. It would be important to determine whether quality differences between surface and groundwater sources are impacting productivity, and whether related environmental stresses, such as salinity problems from excessive groundwater use, are key factors suppressing yield gains.

Notes

1. Only 2% of the households in the sample were on watercourses at the head of a distributary; these are combined with the middle location on the distributary.
2. One acre-foot is 1233.48 m^3.
3. An acre of land is equivalent to 0.405 ha.
4. This is because elasticity can be shown to be a ratio of marginal product of an extra input and average product of the total input used so far.

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