Journal of Hydrology 527 (2015) 50–61

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

The effect of private tubewells on income and income inequality in rural Pakistan

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ARTICLE INFO

Article history:
Received 9 December 2014
Received in revised form 15 April 2015
Accepted 17 April 2015
Available online 27 April 2015
This manuscript was handled by Geoff Syme, Editor-in-Chief, with the assistance of V. Ratna Reddy, Associate Editor

Keywords:
Tubewell
Irrigation
Income
Income inequality
Pakistan

SUMMARY

Since the introduction of private tubewells in rural Pakistan, farmers have increasingly used groundwater to supplement canal water for irrigation and improve the reliability of the water supply. Farmers obtain groundwater either from their own tubewells or from other well owners. This paper examines the effect of private tubewells on rural income, both in terms of income level and income distribution since it may differ across farmers with different irrigation status (only canal water, canal water and groundwater from own tubewell, and canal water and purchased groundwater). The results show that private tubewells work to enhance rural income and reduce income inequality in rural Pakistan.

1. Introduction

Agriculture is a vital part of Pakistan's economy. It accounts for 21.6% of the nation's GDP in 2009 and employs more than 40% of the labor force (World Bank, 2012). Pakistan's agriculture relies on irrigation much more than most other countries. More than 80% of its cultivated area is irrigated (Kamal, 2009). In rural Pakistan, farmers used to rely solely on the public irrigation system, including a network of canals and public tubewells, for irrigation water. Farmers took turns to use water from the public irrigation system. The turns were fixed based on the locations of plots owned by farmers (Meinzen-Dick, 1996). However, the canal network often failed to supply water with sufficient quantities or at the times needed. Meanwhile, the performance of public tubewells also deteriorated due to a lack of funding for operation and maintenance (Chaudhry and Young, 1990).

In response to the inadequacy and the unpunctuality of the public irrigation system, private tubewells have emerged to supplement the public water supply, especially the canal water supply. Farmers either sink their own tubewells or purchase water from other farmers that own tubewells. The groundwater markets in rural Pakistan are informal since usually there are not any legal sanctions (Meinzen-Dick, 1996). The rise of tubewells could have a positive impact on household income because more reliable water supply is likely to increase crop yields. A relatively large literature exists in India that examines the impact of groundwater market on income (e.g., Kajisa and Sakurai, 2005). However, there is not a large literature that looks at tubewell irrigation in Pakistan. Meinzen-Dick (1996, 1998) found that wheat yields of farmers that had their own tubewells were higher than those of other farmers. However, household income does not always respond positively to the rise of tubewells due to factors such as fluctuating energy costs and declining groundwater levels in the long term. So the effect of tubewells on income becomes an empirical question. For the rest of the paper, tubewells refer to private tubewells unless otherwise noted.

In addition to its effect on the level of income, how the spread of tubewells influences the income inequality is also of concerns to policy makers. Both scholars and policy makers have come to recognize that in addition to income levels, income inequality also matters for poverty reduction (e.g., Atkinson, 1997; Fields, 2002; Sekhri, 2014). Income inequality is usually measured using the Gini coefficient, with the value of 0 indicating perfect equality and 100% indicating perfect inequality. Zaman and Khilji (2013)

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http://dx.doi.org/10.1016/j.jhydrol.2015.04.034
0022-1694/

shows that a 1% increase in the Gini coefficient while holding the income level constant increases poverty by more than 1% in Pakistan. This is because although the average income level is the same, a higher inequality level means more income is shared among fewer households and thus more households are left below the poverty line. In addition, rising inequality can negatively affect poverty reduction if it impedes economic growth (Naschold, 2009).

The spread of tubewells has the potential to change the income distribution in rural Pakistan. The costs of tubewell installation and pumping equipment purchase often prevent small and poor farmers from owning a tubewell (Meinzen-Dick, 1996). If only wealthy farmers benefit from tubewell irrigation because they can afford to invest in tubewells and thus expand their irrigated areas, the rise of tubewells is likely to exacerbate income inequality. However, poor farmers could also benefit from the spread of tubewells if they can purchase groundwater through groundwater markets. Thus, whether income inequality will rise or drop depends on the extent to which poor farmers can benefit from tubewell irrigation. If tubewell owners have strong monopoly power and farmers are forced to pay much higher water prices, groundwater markets may reinforce the disparity between tubewell owners and non-owners (Qureshi et al., 2003). Tubewell ownership and groundwater market may also worsen income inequality at the regional level because excessive drawdown in the upstream may lead to less water being available downstream. Since tubewells can influence income inequality through the various channels, it is important to quantify the impact of tubewells on income inequality. This is particular important to policy makers in Pakistan given its high poverty rate, especially in rural areas. In 2008, 60% of Pakistan's population was living below the poverty line defined as $2/day, a rate that is much higher than other countries in the same region such as Sri Lanka (23.9%, World Bank, 2013).

A group of researchers have studied income inequality in Pakistan (e.g., De Kruijk, 1987; Adams, 1994; Adams and He, 1995; Shams, 2012). Most of these studies are descriptive in nature and only decompose income inequality by income components such as off-farm income and crop income. Only a few studies (e.g., Naschold, 2009) examine how the determinants of income such as education and irrigation would affect income inequality. In one of the very few papers that look at the relationship between tubewell irrigation and income inequality, Shaheen and Shiyani (2005) find that income was more equally distributed in the Mehsana district than in the Banaskanth district in North Gujarat. Their explanation is that farmers have more equal access to groundwater in the Mehsana district. However, no quantitative analysis is done to control for the influence of other factors such as off-farm employment.

Outside Pakistan, there is a large literature that examines groundwater market, epically in India, which is now the largest groundwater economy in the world (Shah, 2008). The record on the impacts of groundwater markets is mixed (e.g., Mukherji, 2004; Singh and Singh, 2003). In general, there is a consensus that groundwater markets boost water productivity through channels such as higher crop intensity and higher crop yields (e.g., Shah, 1993). Meanwhile, scholars also debate on whether groundwater market is monopolistic in nature and whether water buyers are being exploited through higher water prices charged by tubewell owners. Fujita and Hossain (1995) argue that the high water charge is reasonable when the high interest rates in the local informal financial market are taken into account and conclude that the development of groundwater markets does not necessarily worsen income disparity. Kajisa and Sakurai (2005) find that the bargaining power of the buyers, not the sellers, is more important in price determination because it is difficult to prevent the entry of new groundwater sellers. Banerji et al. (2012) find that water trades result in a spatially-efficient allocation of water and a social contract exists to determine both water price and water allocation in groundwater markets. Kumar et al. (2011) find that establishing an energy quota at farm level based on sustainability considerations, metering and charging pro rata for power could lead to efficient use of water and energy, and equity in access to groundwater. Although previous studies touch on the issue of equity, most focus on indirect measures such as groundwater prices (e.g., Kajisa and Sakurai, 2005). Our study is among the very few that examine the impact of groundwater markets on the direct measure of income inequality.

The overall goal of this paper is to answer two interrelated questions. First, how do tubewells influence individual farmers in terms of their income? Second, how do tubewells influence the rural community as a whole? Specifically, how does the rise of tubewells affect income inequality in rural Pakistan? We will answer these questions using a data set that contains information on irrigation in the crop seasons during year 2010–2011. To our knowledge, the data set we use is probably the most recent data on tubewell irrigation in Pakistan. The findings from this study will help policy makers determine whether to support the trend of rising private tubewells or to intervene. If tubewells could increase income levels without increasing income inequality, the spread of tubewells should be encouraged by government interventions such as subsidies for tubewell installment and extension efforts to help set up and operate water markets. Otherwise, policy makers ought to balance the positive effect of tubewells on income and their negative effect on income distribution.

The rest of the paper is organized as follows. Section 2 describes the data set that forms the basis of the analysis and characteristics of farmers in the sample area. Section 3 first presents the methods we use to examine the effect of tubewell irrigation on income and then reports the empirical results. Section 4 analyzes the effect of tubewell irrigation on the income inequality in rural Pakistan. The final section concludes.

2. Survey data and descriptive analysis

Data for this study come from a household survey conducted by the International Water Management Institute (IWMI) in 2012 in the most populous province of Pakistan, the Punjab province. There are more tubewells in Punjab than any other regions in Pakistan. In 2002, it was reported that there were 566,446 tubewells in Punjab and almost 90% of wells were equipped with diesel pumps (Qureshi et al., 2003). Although electricity pumps are usually more profitable, diesel pumps are more common in Pakistan, which is probably due to the limited availability of electricity and high replacement cost of electric pumps (Aurangzeb, 2007). The sample area of the survey is the Hakra branch canal of the Bahawalnagar District in Punjab (Fig. 1). Although the focus of the survey is on tubewell irrigation, return flows from canal irrigation need to be taken into account because seepages from unlined canals and irrigated fields have been significant sources of recharge of groundwater in the region (Ahmad et al., 2007). Because of the connection between canal irrigation and groundwater, locations relative to sources of canal water supply are important. The sampling framework of the survey takes this into account. A stratified random sampling strategy was used to select sample distributaries with varying degrees of water scarcity, which was highly correlated with the distance to the head of the Hakra Branch. Three sample distributaries were selected. The Khatan distributary is located at the head reach and has 129 watercourses in total. In most sample villages, the whole village uses water from the same watercourse. The Mamun distributary is in the middle reach and has 129 watercourses. The Sardrewala distributary is in the tail reach and has 106 watercourses. Each distributary was then divided into three sections: the head, the middle and the tail reaches. Around

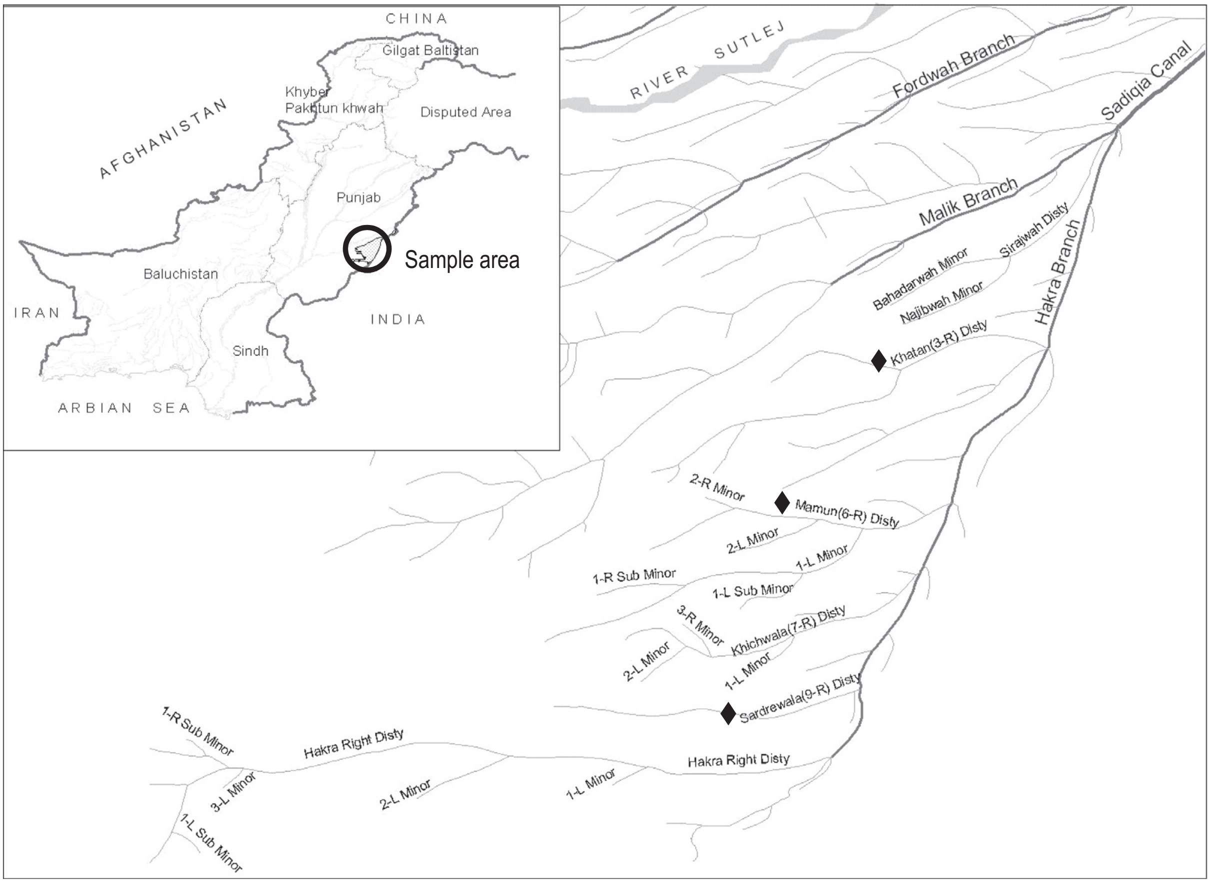

Fig. 1. Location of the Bahawalnagar District in Pakistan (market by ○) and the sample distributaries (marked by ♦). *Source*: International Water Management Institute.

Table 1
Crop mix and type of irrigation.

Crop[a]	% of sown area irrigated by[b]				
	(1) % of sown area	(2) Canal water only	(3) Canal water and water from own tubewell	(4) Canal water and purchased groundwater	(5) = (2) + (3) + (4) % of irrigated area in crop
Grain	49.6	13.8	14.5	70.3	98.6
Include: Wheat	42.4	14.2	14.6	69.7	98.5
Cash crop	40.9	14.0	15.8	68.8	98.6
Include: Cotton	39.8	13.8	15.8	69.0	98.6
Fodder	9.4	20.5	13.5	65.2	99.2
Include: Lucern	7.1	20.2	9.6	69.3	99.1

[a] The categories of fruits and vegetables are not reported since they only take a small share in the crop mix.
[b] The category of rainfed is not reported since they only take a small share in irrigation.

nine watercourses were randomly selected from each section of the distributaries. Within each watercourse, approximately nine farmers were randomly selected for interviews. In total, 750 farmers were interviewed. The sample period covered both crop seasons in year 2010–2011: the Rabi season (October 2010–April 2011) and the Kharif season (April 2011–October 2011). The survey collected crop-level information such as crop mixes, yields and sources of irrigation (canal water or groundwater), plot-level information such as land ownership, soil quality and distance to watercourse channel. Household demographic information such as age, household size and education and social-economic characteristics such as off-farm employment, land holding and income were also collected. In addition, the survey also collected information on the characteristics of water resources such as water quality and the characteristics of tubewells and watercourses. In all analysis in this paper, sampling weights are used to weigh observations in regression analysis.

Table 1 shows that sample farmers grow multiple crops. The crop mix in the sample area includes grain crops (49.6% of the sown area), cash crops (40.9%) and fodder crops (9.4%). Fruits and vegetables are also grown but only on a few plots. The major grain crop is wheat (42.4%). Other grain crops include millet and sorghum. The major cash crop is cotton (39.8%). Other cash crops include rapeseed, mustard and sugarcane. The major fodder crop is lucern (i.e., alfalfa, 7.1%). The cotton–wheat rotation is used on nearly 90% of the cultivated area with wheat grown in the Rabi season and cotton in the Kharif season (Mayee et al., 2008). It should be noted that nearly 60% of precipitation falls in the monsoon season (July–September), which overlaps with the Kharif season (Muslehuddin et al., 2005).

Farmers irrigate their crops in multiple ways. Because the sample area is in the command area of the public canal system in the Bahawalnagar District, all plots have access to canal water. Farmers could rely solely on the public canal system to irrigate some or all of their crops. When tubewells are available, farmers in rural Pakistan often use groundwater primarily to supplement canal water in irrigation (Murray-Rust and Vander Velde, 1994). Farmers use canal water and groundwater conjunctively in two ways. In most cases, farmers first mix canal water with groundwater before applying them simultaneously to irrigate crops. This is because the quality groundwater quality is generally poorer than that of canal water in the sample area. Mixing groundwater with canal water improves the quality of irrigation water. In other cases where groundwater is fit or marginally fit for irrigation, farmers apply groundwater directly to irrigate crop without mixing it with canal water. In these cases, groundwater is used when canal water is not available. The choice over the two variations is determined by the rigidity of canal water allocation scheme, the reliability of canal water and crop mixes. To simplify our analysis, in this paper, we do not distinguish between these two different ways of conjunctive uses.[1]

Nearly all tubewells in the area are private, that is, wells are owned by farmers instead of the government. Most private tubewells are owned by individual farmers. Only a few are owned jointly by a group of farmers. In the sample area, the average number of tubewells per farmer is 0.20. Given that most tubewell owners only have one well, this means approximately one out of five farmers has tubewells. In addition, almost half of the tubewell owners (46%) sell tubewell water to other farmers in the villages. Groundwater market activities are mostly informal because farmers trade with only oral commitments, without any contract or any other legal sanctions. Informal groundwater market activities are also prevalent in other Asian countries such as India and China (Shah, 2008; Zhang et al., 2008). In the rest of the paper, farmers are divided into three groups: tubewell owners, water buyers and canal-only users. In addition to using canal water, tubewell owners irrigate with water from their own tubewells. This group also includes the owners that sell water to other farmers. Water buyers irrigate with canal water and water bought from tubewell owners. Canal-only users only use water supplied by the public canal system.

Table 1 shows the importance of tubewell irrigation in the irrigated agriculture in Pakistan. More than half of the sown area is irrigated conjunctively by canal water and purchased groundwater (e.g., 70.3% for grain crops, 68.8% for cash crops and 65.2% for fodder crops). About half of the remaining sown area (between 9.6% and 15.8%) is irrigated conjunctively by canal water and groundwater from own tubewells. Only between 13.8% and 20.5% of the sown area is irrigated solely by canal water.

Table 2 reveals differences among different types of water users. Tubewell owners appear to be wealthier, with their individual income almost twice as much as that of canal-only users. In this paper, all sources of income (e.g., total income and crop income) are calculated as net income after cost is subtracted. They have larger land holdings per capita (2 acres) than water buyers (1.5 acres) and canal-only users (1.5 acres). Tubewell owners are more likely to get a loan and are more educated than other users, both of which are probably related to their wealth. These observations are consistent with findings in India that large land lords are more likely to own tubewells and in China that tubewell owners have higher household income (Shah, 1993; Zhang et al., 2008). However, it also raises the concern that small land holders or poor households (these two are often the same group) may not benefit from the increased access to groundwater.

Another difference is that tubewell owners are less engaged in off-farm employment. In the households of tubewell owners, only 7.6% of the household members work full time off-farm. This is in contrast to 10.5% in the households of water buyers and 14% in the households of canal-only users. The difference may arise because the labor required to operate tubewells reduces labor available for off-farm jobs. It may also arise because tubewells allow owners to increase farm income (including both crop income and livestock income) and thus reduce their tendency to seek off-farm income. The crop income of tubewell owners is 65% higher than that of water buyers and more than twice as much as that of canal-only users.

Compared to canal-only users, groundwater underlying the land of tubewell owners and water buyers has relatively better quality. Groundwater salinity is measured by electricity conductivity (EC). The average EC level of groundwater under the land of tubewell owners is 2538.7 mmhos/cm, which means the water is moderately saline and suitable for irrigation with sufficient leaching (Beg and Lone, 1992). In contrast, the average EC level of groundwater under the land of canal-only users is 3278.7 mmhos/cm, which indicates that the water is severely saline and may harm the growth of crops if used for irrigation. This difference in water quality makes sense, because farmers are only sinking wells where they can get access to relatively less saline groundwater. Tubewell owners also have better soil than other users. When we compare the location of the farmers, tubewell owners are more likely to be located in the watercourses in the head or middle reaches of the sample distributaries than water buyers or canal-only users.

There are fewer differences between canal-only users and water buyers. Education, total income, land holdings per capita and credit access do not differ much between these two groups. Water buyers have higher crop incomes and the difference is statistically significantly at 5%. The difference in crop income may be attributable to the higher cultivated acreage water buyers have in both wheat and cotton, although only the difference in the acreage in cotton is statistically significant. Since the two groups of farmers have similar sizes of land holdings, the difference in access to irrigation may explain the difference in cultivated acreage.

As expected, Table 3 shows that tubewell provides more reliable water supplies than the canal network, both in terms of the quantity and the timing. Almost 60% of tubewell owners always get the full amount of groundwater needed and 42.6% always get groundwater at the time needed. In contrast, only around 15% of canal-only users always get the quantity of canal water required or at the time needed. However, there is no clear evidence to support that access to groundwater has increased the reliability of water supply for water buyers relative to canal-only users. The share of water buyers that always get the full amount of water is only slightly higher than that of canal-only users (16.8% versus 14.9%). The share of water buyers that never or only occasionally get the full amount of water is also close to that of canal-only users (23.4% versus 25.1%). The same is true for the share of water buyers that always get water at the times needed.

The differences in the quantity, quality and reliability of the water supply could affect the crop choices of farmers.[2] Crops vary in their sensitivity to the quantity and quality of water. For instance, grain crops such as wheat and millet are more tolerant to salinity but cash crops such as cotton and sugarcane are sensitive to salt (Tanji

[1] In some regression specifications (not reported for the sake of brevity) we include a dummy variable that equals one if farmers mix canal water with groundwater in conjunctive use. The estimated coefficient on this dummy variable is negative and sometimes statistically significant in income regressions. However, estimated coefficients on the key variables of interest are not affected with the inclusion of this dummy variable.

[2] The volumetric prices of canal water and groundwater are likely to be different. The IWMI survey was not able to collect information to calculate the volumetric prices of either canal water or groundwater. This is because most farmers did not know the flow rate in the canals that supplied water to their plots. Most water buyers did not know the flow rate of the pumps of the well owners that sold them water. So we could not calculate the volume of water applied, even though the payment information is available. Field observations suggest that in most areas, canal water is cheaper than groundwater. In regression analysis, the use of watercourse fixed effects helps control for variations in prices at the watercourse level.

Table 2
Characteristics of sample farmers by type of water users.

	(1) All farmers	(2) Canal-only user	(3) Tubewell owner	(4) Water buyer	Difference (3) – (2)	(4) – (2)	(4) – (3)
Household size	8.1	8.1	8.4	7.8			***
	(3.4)	(4.0)	(3.6)	(2.9)			
Age of household head (year)	45.6	45.5	44.9	46.2			
	(13.6)	(14.0)	(13.2)	(13.8)			
Education level of household head in school (year)	7.2	6.6	7.9	6.8	***		***
	(4.0)	(4.3)	(3.8)	(4.0)			
Percent of household labor working full time off-farm	9.8	14	7.6	10.5	***	*	**
	(21.8)	(24.7)	(20.2)	(22.2)			
Total income per capita (1000 Rs)	54.2	36.2	70	46.2	***		***
	(77.8)	(41.8)	(83.1)	(78.8)			
Crop income per capita (1000 Rs)	32.9	17.2	45	27.3	***	**	***
	(52.0)	(29.3)	(64.7)	(42.4)			
Crop income per acre (1000 Rs)	11.2	8.2	12.7	10.9	***	***	**
	(9.9)	(9.0)	(9.5)	(10.2)			
Livestock income per capita (1000 Rs)	12.0	7.3	16.3	9.9	***		***
	(26.7)	(13.9)	(32.7)	(23.3)			
Off-farm income per capita (1000 Rs)	6.7	9.1	6.9	5.9		**	
	(16.6)	(16.9)	(17.8)	(15.5)			
Percent of crop income in total income	61.8	51.8	66.2	60.9	**	**	*
	(51.4)	(42.9)	(55.7)	(49.5)			
Percent of off-farm income in total income	13.1	23.5	8.6	13.9	***	***	**
	(38.7)	(38.0)	(41.9)	(35.5)			
Can get a loan of Rs 3000 without any difficulty (%)	56.8	51.0	64.7	51.8	***		***
	(49.6)	(50.2)	(47.9)	(50.0)			
Can get a loan of Rs 6000 without any difficulty (%)	40.7	35.7	49.2	35.0	**		***
	(49.2)	(48.2)	(50.1)	(47.8)			
Land holding per capita (acre)	1.7	1.5	2.0	1.5	**		***
	(1.8)	(2.6)	(1.8)	(1.5)			
Area cultivated in wheat (acre)	7.6	5.7	9.9	6.2	***		***
	(7.4)	(7.9)	(8.5)	(5.6)			
Percent of area cultivated in wheat	41.8	42.4	41.7	41.7			
	(9.5)	(10.9)	(8.8)	(9.8)			
Area cultivated in cotton (acre)	7.3	4.6	9.8	6.1	***	***	***
	(7.1)	(3.9)	(8.6)	(5.7)			
Percent of area cultivated in cotton	39.4	39.5	38.9	38.9			*
	(9.3)	(9.5)	(8.8)	(9.6)			
Percent of area with soil quality above average	42.9	37.6	46.5	41.4	*		*
	(48.2)	(47.7)	(48.3)	(48.3)			
Percent of area with moderate or high soil salinity	31.6	27.2	31.5	33.0			
	(44.3)	(43.2)	(43.6)	(45.3)			
Degree of land fragmentation (number of plots)	1.3	1.2	1.4	1.2	***	*	***
	(0.5)	(0.4)	(0.6)	(0.5)			
Groundwater salinity in 2012 (mmhos/cm)	2791.9	3278.7	2538.7	2867.6	***	***	***
	(1135.9)	(1664.0)	(841.1)	(1118.9)			
Watercourse in head reach of distributary (%)	36.1	34.7	27.3	32.2			***
Watercourse in middle reach of distributary (%)	31.2	28.6	54.5	30.3			
Watercourse in tail reach of distributary (%)	32.7	36.7	18.2	37.5	**		***

Notes: Rs is the abbreviation for Rupees, the currency used in Pakistan. In 2011, 1 dollar was about 85 Rs.
* Significance at 10%.
** Significance at 5%.
*** Significance at 1%.

Table 3
Delivery reliability and productivity by types of water users.

	Canal-only user	Tubewell owner	Water buyer
Delivery reliability: Percent of users			
Always get full amount of water	14.9	59.1	16.8
Never or occasionally getting full amount of water	25.1	15.4	23.4
Always get water at the times needed	14.9	42.6	13.2
Never or occasionally get water at the times needed	26.5	28.9	29.9
Output value: 1000 Rs/acre			
Wheat	26.3	30.8	29.1
	(9.1)	(20.6)	(8.5)
Cotton	31.5	39.9	35.5
	(14.7)	(28.7)	(14.9)

and Kielen, 2002). Cash crops such as rapeseed are drought tolerant (Tanji and Kielen, 2002). Wheat is moderately sensitive to drought, while millet is less sensitive (Brouwer et al., 1989; Haman, 2000). Table 1, however, reveals no apparent difference in crop mixes among the three types of farmers. Most farmers follow the wheat–cotton rotation on their land. This may be due to the trade-off between the quantity and the quality of water when using groundwater. Tubewell owners and water buyers could augment the quantity of irrigation water by accessing groundwater. However, they also have to endure the lower quality associated with groundwater in the area. The access to groundwater could enable users to diversify into growing more cash crops. In terms of area size, we observe that canal-only users grow less cotton than wheat, while the wheat and cotton areas are about the same for both tubewell owners and water buyers. However, in terms of percent of cultivated area we do not observe that canal-only users grow apparently less cotton than wheat, compared with tubewell owners and water buyers.

Table 3 does show that tubewell owners and water buyers enjoy higher output values per acre than canal-only users. Tubewell owners have the highest output value for both wheat and cotton. This is consistent with the findings that they have the most reliable water supply through their own tubewells. The output values of both wheat and cotton generated by water buyers are also higher than those of canal-only users. It is likely that although tubewell irrigation does not seem to increase the reliability of water supply for water buyers, buyers are able to augment the quantity of irrigation water and thus obtain higher output values from their fields.

3. Impact of tubewell irrigation on income

3.1. Model specifications

Following Paxson (1992) and other studies in the literature (e.g., Zhang et al., 2010), we use the following model to examine the factors that influence household income:

$$y_{ij} = \alpha_j + \boldsymbol{D}_{ij}\boldsymbol{\beta} + \boldsymbol{H}_{ij}\boldsymbol{\gamma} + \boldsymbol{L}_{ij}\boldsymbol{\theta} + \varepsilon_{ij}, \tag{1}$$

where y_{ij} is the annual total net income per capita of household i in watercourse j. The vector $\boldsymbol{H}_{ij}$ contains household characteristics including age, education, caste, household size and off-farm employment. Variables in vector $\boldsymbol{L}_{ij}$ measure land and water characteristics such as the degree of land fragmentation, soil quality, land holding and groundwater quality. The fixed effects at the watercourse level, denoted by α_j, capture all watercourse level and regional level characteristics that are time invariant, including all observable and unobservable factors such as locations and the rate of return flow. That is, in our analysis, the comparison of income between different groups (canal water users, tubewell owners and water users) is made controlling for factors such as the rate of return flow. The key variables of interest are in the vector, $\boldsymbol{D}_{ij}$, which includes two dummy variables. The first dummy variable equals one for tubewell owners (including groundwater sellers). The second dummy variable equals one for water buyers. Canal-only users are the base group in Eq. (1).

The dummy variables used in Eq. (1), however, may not accurately describe the irrigation status of farmers because some tubewell owners have multiple plots. Tubewell owners may not have a well located near each of his/her plots. So they may also buy water to irrigate crops on the plots near which they have not sunk their own wells. Therefore, in an alternative specification, two continuous variables are used to measure the irrigation status:

$$Y_{ij} = \alpha_j + \boldsymbol{S}_{ij}\boldsymbol{\beta} + \boldsymbol{H}_{ij}\boldsymbol{\beta} + \boldsymbol{L}_{ij}\boldsymbol{\beta} + \varepsilon_{ij}. \tag{2}$$

In Eq. (2), the key vector in (1), $\boldsymbol{D}_{ij}$, is replaced by $\boldsymbol{S}_{ij}$, which includes two variables: the percent of area irrigated by water from own tubewells and the percent of area irrigated by water purchased from others' tubewells. For both Eqs. (1) and (2), additional specifications are also run with crop income per capita as the dependent variable.[3]

[3] Given that the size of land holdings differs across farmers with different irrigation status, we also run specifications where total income per acre or crop income per acre is the dependent variable. The results are largely the same. The magnitudes of the coefficients on income per acre are smaller, which is expected because income per acre is smaller than income per capita in size (in sample data, on average number of acres is higher than number of people in the household). The signs and levels of significance remain the same. We also rerun the regressions in Tables 4 and 5 using total income and total crop income as the dependent variables. The signs and levels of statistical significance of the estimated coefficients on the key variables that measure well ownership are largely the same as in the regressions that use income per capita as the dependent variables. The sizes of the estimated coefficients are larger by about one order of magnitude, which is expected because the dependent variables are larger by about one order of magnitude. We focus on the results on income per capita because this is the form of income usually used in calculating income inequality.

A potential econometric issue with estimating Eqs. (1) or (2) is the endogeneity of the key variables that measure the irrigation status, $\boldsymbol{D}_{ij}$ in (1) and $\boldsymbol{S}_{ij}$ in (2). Reverse causality may exist because income may influence tubewell ownership: income is often highly correlated with wealth, and wealthier farmers are more likely to be tubewell owners because they can afford the cost of installing wells and purchasing equipment. If this reserve causality does exist, the estimated coefficients on the variables that measures tubewell ownership will be upward biased. There may also be some omitted variables. Farmers' decision to sink a tubewell also depends on local conditions that affect agricultural productivity. Although we have included variables such as soil quality, water quality and a set of watercourse fixed effects to control for agricultural productivity, there may still be some characteristics of the locality that affect income and are also correlated with the right hand side variables in the regression. For example, the reliability of canal water delivery in the past would affect farmers' decision to sink wells. Failure to control for such factors could cause a downward bias in the estimated coefficients on variables that measure tubewell ownership.

When the Davidson–Mackinnon test is applied to sample data (Davidson and MacKinnon, 1993), the null hypothesis that there is no endogeneity is rejected. To address this issue, we instrument for the variables that measure tubewell ownership using two variables: the average distance from a farmer's plot to the nearest well that does not belong to the farmer and hours needed to fully irrigate one acre of the farmer's plot using water from canals. The two conditions an instrumental variable needs to satisfy are: (1) The variable is correlated with the endogenous variable; (2) The variable is uncorrelated with the error term (Wooldridge, 2010). If a farmer's plot is far away from others' tubewell, it will be difficult or even impossible to obtain groundwater from these wells because tubewell owners often sell groundwater only to farmers nearby due to conveyance losses and/or lack of equipment to transport groundwater to a far distance. Thus the longer is the distance, the more likely a farmer is to sink his own tubewell. Except through its influence on a farmer's decision to sink a well, the distance to others' wells is unlikely to affect a farmer's income because the locations of others' wells are not determined by the farmer. In addition, we have included a set of watercourse fixed effects that capture characteristics of locality including water resources at the watercourse level. Then the characteristics of locality that may be correlated with the distance variable (e.g., the general quality of groundwater that may affect the density of tubewells at a particular location) are included in the regression and thus are not left in the error term. Then the distance variable is not likely to be correlated with the error term. Similar argument can be applied to the second IV. Hours needed to completely irrigate one acre of land reflects the farmer's specific irrigation needs in terms of timing or water quantity or both. If more hours are needed, the fixed irrigation schedule under the public water supply is unlikely to satisfy irrigation needs. Thus groundwater supply is more attractive to farmers because it renders more control to farmers to make sure their irrigation needs are met. Since the number of hours needed for complete irrigation of one acre of land using water from canals is mostly influenced by factors such as flow rates in the canals, we think they do not have a strong influence on income except through their influence on the decision of farmers to sink tubewells. Furthermore, flow rates in the canals are not likely to vary much at the watercourse level and are captured by the watercourse fixed effects. So we think it is reasonable to assume that the hours variable is not correlated with the error term either. This is supported by the Hansen's *J* statistic (1982), which tests for the correlation between IVs and error terms. The Hansen's *J* statistic (1982) shows that the instrumental variables (IVs) used are valid in the regressions. In short, both variables satisfy the conditions required for IV estimation.

Multicollinearity problem may arise in the regression. In the IWMI survey, when farmers that never installed a tubewell were asked to report reasons, poor groundwater quality is cited as the main reason (53% of the farmers). Cost of sinking tubewells is the second most cited reason (21%). We use the condition index to detect the presence of multicollinearity among explanatory variables. Belsley et al. (1980) show that a condition index of 5–10 reveals weak dependencies while a number of 30–100 is associated with strong to severe collinearity (multicollinearity). The largest condition index is 8.77, which says we do not have a multicollinearity problem. The diagnostic also indicates that the source of collinearity that leads to the condition index of 8.77 is likely to be the correlation between household size and age of household head. In short, the correlation between groundwater quality and tubewell ownership does not result in multicollinearity problem.

3.2. Regression results

Tables 4 and 5 report the results of estimating Eqs. (1) and (2) that examine the determinants of total income and crop income per capita. The adjusted R-squared for most specifications are above 0.2, which is reasonable for estimation using a set of cross-sectional data. The estimated coefficients on most control variables are of the expected signs. For example, a larger land holding has a positive and statistically significant impact on both crop income and total income. A higher degree of land fragmentation (separated into too many plots) is likely to lower both crop income and total income and the negative effects are statistically significant. Soil with higher salinity also lowers both crop income and total income. In Table 5 where percent of irrigated area is used to measure irrigation status, the results also show that if more of the household labor works full time off-farm, income tends to be higher. In both Tables 4 and 5, education is shown to have a positive and statistically significant impact on both to total income and crop income. One more year of schooling increases total income by about 2700 Rs and crop income by about 1600 Rs.[4] The positive link between total income and education is well established in the literature (e.g., Paxson, 1992). The link between education and crop income is not always present. In the case of rural Pakistan, it may be that education enables farmers to improve agricultural skills more easily and apply more efficient cultivation techniques.

Results of the IV regressions show that there may be downward bias in the estimated coefficients from the OLS regressions. The IV estimates of the coefficient on the variable tubewell owner are larger than the OLS estimates by several folds (Table 4). The IV estimate of the coefficient on the variable percent of area irrigated is also larger than the OLS estimate by several folds (Table 5). Standard errors in IV regressions are also much larger than in OLS regression. This is expected because only a portion of the variation in the endogenous variables (the exogenous variation purged out by the IVs) is used in regression. This will lead to larger standard errors.

Both Tables 4 and 5 provide evidence to support the positive impact of tubewell irrigation on crop income. Table 4 shows that, compared to canal-only users, owning a tubewell increases crop income per capita by Rs 178,600 and total income per capita by Rs 241,300. Both effects are statistically significant. The increase in total income is more than the increase in crop income, perhaps because some tubewell owners also gain additional income from selling groundwater. Being a water buyer also earns higher crop income. This is probably because tubewell irrigation allows water buyers to augment the quantity of water supply. The magnitude of increase water buyers enjoy is, however, smaller than that of the tubewell owner. This is consistent with findings in Table 3 that the reliability of water supply for water buyers is only slightly better than that of canal-only users and significantly below that of tubewell owners.

Table 4
Regression of the determinants of income (1000 Rs per capita) – Model (1).

	Total income per capita		Crop income per capita	
	OLS	IV	OLS	IV
Tubewell owner	21.96***	241.3*	15.37***	178.6*
	(8.359)	(128.8)	(5.552)	(105.6)
Tubewell water buyer	4.525	204.3*	12.47**	161.2*
	(7.482)	(119.4)	(5.630)	(95.77)
Household size	0.272	−0.992	1.184	0.243
	(1.363)	(1.517)	(0.812)	(1.151)
Age of household head (year)	0.339	0.328	0.164	0.156
	(0.224)	(0.265)	(0.132)	(0.166)
Education level of household head (years of schooling)	2.722**	2.757**	1.600**	1.626**
	(1.163)	(1.271)	(0.632)	(0.759)
Percent of household labor working full time off-farm	0.156	0.311**	0.110	0.225**
	(0.0978)	(0.133)	(0.0682)	(0.108)
Caste is Arian	−14.44	−16.77	−1.274	−3.007
	(12.03)	(11.79)	(5.208)	(5.958)
Groundwater salinity in 2012 (mmhos/cm, standardized)	−10.99	−5.034	−6.824	−2.388
	(8.551)	(11.02)	(5.543)	(7.829)
Degree of land fragmentation (number of plots)	−9.096	−14.88*	−14.71***	−19.01***
	(6.957)	(8.602)	(5.284)	(6.191)
Percent of area with above average soil quality	0.0483	0.00656	−0.00534	−0.0364
	(0.0663)	(0.0764)	(0.0528)	(0.0609)
Percent of area with moderate or high soil salinity	−0.114*	−0.113	−0.118**	−0.117**
	(0.0641)	(0.0725)	(0.0471)	(0.0522)
Land holding per capita in acre	29.14***	26.89***	25.34***	23.67***
	(4.526)	(4.318)	(3.788)	(3.779)
Watercourse fixed effects	Yes	Yes	Yes	Yes
Observations	744	744	744	744
Adjusted R-squared	0.437	0.075	0.508	0.163

Notes: Standard errors in parentheses (clustered at the watercourse level).
* Significance at 10%.
** Significance at 5%.
*** Significance at 1%.

Findings from Table 5 are consistent with those from Table 4. A one percentage point increase in the area irrigated by water from own tubewell adds Rs 1822 to total income per capita and Rs 1427 to crop income per capita. The increments are 2.6% of total income and 3.2% of crop income respectively. A one percentage point increase in the percent of area irrigated by water purchased from tubewell owners increases the total income of water buyers by Rs 1491, which is 3.2% of their total income. A one percentage point increase in the percent of area irrigated by water purchased from tubewell owners increases the crop income of water buyers by Rs 1271, which is 4.6% of their crop income. So proportionally water buyers benefit more from tubewell irrigation than tubewell owners in terms of both total income and crop income.

4. Impact of tubewell irrigation on income inequality

Since the groundwater markets are active in the sample area, there is clearly a positive spillover of tubewells on non-owners. However, the regression results in the previous section show that tubewells increase the crop income and total income of owners more than those of non-owners. This raises concerns that the spread of tubewells could enlarge the disparity between the rich

[4] Rs is the abbreviation for Rupees, the currency used in Pakistan. In 2011, one dollar was about 85 Rs.

Table 5
Regression of the determinants of income (1000 Rs per capita) – Model (2).

	Total income per capita		Crop income per capita	
	OLS	IV	OLS	IV
Percent of area irrigated by water from own tubewell	0.212**	1.822**	0.155***	1.427*
	(0.0858)	(0.908)	(0.0582)	(0.808)
Percent of area irrigated by purchased groundwater	0.0438	1.491*	0.128**	1.271*
	(0.0830)	(0.837)	(0.0593)	(0.722)
Household size	0.302	−0.822	1.172	0.284
	(1.357)	(1.440)	(0.816)	(1.113)
Age of household head (year)	0.333	0.382	0.168	0.207
	(0.225)	(0.275)	(0.132)	(0.183)
Education level of household head (years of schooling)	2.729**	2.890**	1.614**	1.742**
	(1.160)	(1.209)	(0.634)	(0.735)
Percent of household labor working full time off-farm	0.166*	0.378**	0.119*	0.286**
	(0.0988)	(0.151)	(0.0665)	(0.128)
Caste is Arian	−14.24	−15.60	−1.200	−2.276
	(12.02)	(11.76)	(5.197)	(5.843)
Groundwater salinity in 2012 (mmhos/cm, standardized)	−11.58	−7.839	−6.975	−4.022
	(8.511)	(10.57)	(5.439)	(6.874)
Degree of land fragmentation (number of plots)	−9.035	−11.35	−14.54***	−16.37***
	(6.973)	(7.723)	(5.313)	(5.848)
Percent of area with above average soil quality	0.0475	0.00273	−0.00663	−0.0420
	(0.0666)	(0.0728)	(0.0531)	(0.0598)
Percent of area with moderate or high soil salinity	−0.114*	−0.111	−0.118**	−0.115**
	(0.0641)	(0.0760)	(0.0476)	(0.0574)
Land holding per capita in acre	29.19***	27.51***	25.35***	24.03***
	(4.531)	(4.351)	(3.783)	(3.769)
Watercourse fixed effects	Yes	Yes	Yes	Yes
Observations	744	744	744	744
Adjusted *R*-squared	0.436	0.203	0.508	0.258

Notes: Standard errors in parentheses (clustered at the watercourse level).
* Significance at 10%.
** Significance at 5%.
*** Significance at 1%.

and the poor in Pakistan. Similar argument has been raised in previous studies. Adams and He (1995) show that poor farmers have not benefited much from the direct effect of agriculture growth (including irrigation development), because most of the direct and first-round benefits from agricultural growth go to farmers that own lands, who are usually rich. In the case of tubewell irrigation, this can happen if tubewell owners have monopoly power in groundwater markets (Jacoby et al., 2004). They can charge prices far above the marginal cost of supplying groundwater. Then even with the presence of groundwater markets, income inequality may increase because wealthier farmers reap most benefits associated with using groundwater while poor farmers have to pay much more for water. However, there are reasons to believe that tubewell owners may not be able to do so. For example, if demand for groundwater is elastic (e.g., farmers can easily switch to less water-intensive crops or get off-farm jobs), then tubewell owners cannot charge a high price. Moreover, water sellers may not want to exercise the monopoly power. Since both water sellers and buyers reside in the same village, they usually have close social ties. In the sample, 25.8% of water sellers are close relatives or friends of their buyers and more than 40% are neighbors of their buyers. In such settings, even though a higher water price may bring in more revenue, it can also spark tensions in social relationships, which can in turn reduce the social capital that tubewell owners have. Since social capital has been found to influence the income levels of farmers (Narayan and Pritchett, 1999), tubewell owners have incentives to offer acceptable water prices to their buyers. In summary, the presence of tubewell irrigation can move income inequality in either direction, depending on how various factors play. Its effect on the income distribution remains an empirical question.

4.1. Method of decomposition

In this section, we use the most common measure of income inequality, the Gini coefficient. The method used in this paper is developed by Lerman and Yitzhaki (1985), Taylor (1992) and Morduch and Sicular (2002). It has also been used in several studies (e.g. Huang et al., 2005; López-Feldman et al., 2007). We begin by expressing total household income per capita, y, as $y = \sum_{k=1}^{K} y_k$, where y_k is the income from source k (e.g., plots irrigated by canal water, plots irrigated by groundwater). Lerman and Yitzhaki (1985) show that the Gini coefficient for total household income per capita, G, can be written as (Appendix A):

$$G = \sum_{k=1}^{K} R_k G_k S_k, \tag{3}$$

where S_k is the share of y_k in y, G_k is the Gini coefficient that measures the distribution of y_k, and R_k is the Gini correlation between y_k and the distribution of y. The product, $R_k G_k S_k$, is the contribution of source k to the inequality. Eq. (3) decomposes the Gini coefficient for total household income as a weighted sum of the inequality levels of incomes from different sources (G_k), with the weights being functions of the importance of each income source (S_k) and the correlation between each source and total income (R_k). For example, if the income contributed by land irrigated by canal water accounts for a large share of total income (high S_k) and is itself highly unequally distributed (high G_k), then the total income inequality is likely to be high. However, if income from a source is negatively correlated with total income (i.e. this source is more concentrated in the hands of poor farmers, negative R_k), then larger shares of that factor might help equalize total income. Researchers have used formula similar to (3) to examine how various components in total income affect income inequality. Adams (1994) found that livestock income and non-farm income represent inequality-decreasing sources of income in rural Pakistan. Increments in agricultural, transfer and rental income will increase the overall inequality in Pakistan (Adams and He, 1995).

Morduch and Sicular (2002) use a regression-based approach to decompose total income inequality by income flows attributable to specific household characteristics. In their approach, Eq. (3) is still used to decompose income inequality, but y_k is replaced with the estimated income flows measured by the right hand side variables in the regression such as level of education and land holding. For example, the income flows contributed by percent of area irrigated by water from own tubewell and from water purchased from tubewell owners are calculated as $\mathbf{S}_{ij}\hat{\boldsymbol{\beta}}$, where $\hat{\boldsymbol{\beta}}$ is the estimated parameters given by the results from estimating Eq. (2).

The regression-based approach allows us to examine how the change in a particular factor that influences income, such as the presence of tubewell irrigation, household characteristics, and land and water characteristics, will change the income distribution. This approach is advantageous because it provides more intuitive policy implications to policy maker by pointing out which specific factor improves or worsens income distribution. For example, it is natural to think that equitable opportunities and better education will reduce income inequality. However, Hendel et al. (2005) propose that equity-based education policies such as affordable higher education by credit offers and low tuition can exacerbate income inequality. Our empirical results will shed lights on how education affects income inequality in rural Pakistan, which will help policy makers determine whether to use investment in education as a tool to reduce income inequality.

This approach also allows us to assess the marginal effect of a change in a factor on the overall inequality. Stark et al. (1986) show that the elasticity of total income inequality, G, with respect to income source k, y_k, can be written as follows (Appendix A):

$$\frac{\partial G/\partial e_k}{G} = \frac{S_k G_k R_k}{G} - S_k, \tag{4}$$

where e_k is a marginal percentage change in y_k such that $y_k(e_k) = (1 + e_k)y_k$ for all households. Eq. (4) says that the elasticity of income inequality with respect to y_k equals the relative contribution of y_k to the overall income inequality minus the share of y_k in total income.

4.2. Results

Table 6 reports the results of decomposing income inequality based on the regressions in Table 6.[5] The overall Gini coefficient of per capita income estimated for our sample is 0.568. The most recent available data show that the Gini coefficient for Pakistan (nationwide including both rural and urban areas) was 0.3 in 2008 (World Bank, 2012), which is much lower than the Gini coefficient from our sample. This difference may be because the Gini coefficient for the sample province, Punjab province, is higher than other regions in Pakistan. It is also possible that Gini coefficient in rural areas is higher than that in urban areas because in rural areas, one of the most important asset, land, is highly unevenly distributed with some farmers are large landlords while others are landless.

Table 6 shows that tubewell irrigation helps equalize income distribution in the sample area. A 1% increase in the percent of area irrigated by purchased groundwater reduces the Gini coefficient by 2.535%. This shows that tubewell irrigation does not worsen the income distribution. Poor farmers do benefit from groundwater markets. The augmented supply of water allows them to increase the acreage of food crops such as wheat as well as diversify into growing more cash crops such as cotton. By increasing the income of the lower income group, tubewell irrigation narrows the income gap in the region. In other countries such as China, tubewell irrigation has also been found to equalize income distribution (Wang et al., 2009). A 1% increase in the area irrigated by water from own tubewells also reduces the Gini coefficient but by a much smaller magnitude, 0.132%.[6]

[5] The decomposition could be done manually or by using the Stata command, **descogini**, developed by López-Feldman (2006).

[6] We have also investigated the potential deteriorating effect of tubewell ownership and groundwater market on income inequality at the regional level. We can do this because the sampling framework of the survey ensures that farmers from various locations (e.g., heads and tails) are included in our sample, the Gini coefficient measures the income distributions of farmers from all locations (upstream or downstream, farmers from the same watercourse). In addition, in the regression analysis, watercourse fixed effects are used, which capture any watercourse level characteristics that are time invariant, including all observable and unobservable factors such as locations. To do so, we have run a second set of regressions that add the interaction terms between variables that measure tubewell ownership and a dummy that equals one if the farmer is located at the head of the distributary. The results (not reported for the sake of brevity) indicate that the estimated coefficients on the interaction terms are statistically insignificant. Therefore, the income differences between tubewell owners located at the head of distributaries and other tubewell owners are not statistically different. Therefore, the survey data do not offer evidence to support the argument that pumpings by upstream users have impacted downstream users in a way that significantly affected their crop incomes. It should be emphasized that the finding is specific to our study area. It may be because the study area lies above unconfined aquifers and groundwater levels may be more affected by recharges from rainfall and return flows from irrigation than by pumpings of upstream users (Boonstra and Javed, 1999). If different parts of the study area are hydrologically more connected, the findings may be different.

Table 6
Gini decomposition using IV regression results of Model (2).

	S_k	G_k	R_k	*%Change*
Total income per capita		0.568		
Income flows attributed to				
Percent of area irrigated by water from own tubewell	0.235	0.946	0.263	−0.132
Percent of area irrigated by purchased groundwater	2.526	0.289	−0.007	−2.535
Education level of household head (years of schooling)	0.484	0.316	0.203	−0.429
Percent of household labor working full time off-farm	0.105	0.82	0.115	−0.088
Degree of land fragmentation (number of plots)	−0.338	0.155	0.15	0.324
Percent of area with moderate or high soil salinity	−0.083	0.684	−0.076	0.09
Land holding per capita in acre	0.928	0.427	0.523	−0.563

Notes: S_k is the share of each income source in total income. G_k is the Gini coefficient of income from source k. R_k is the Gini correlation of income from source k with the distribution of total income. *%Change* is the impact that a 1% change in the respective income source will have on inequality. Results on other control variables are not reported for the sake of brevity.

Table 6 also points out other factors that could play a role in reducing income inequality in rural Pakistan. Participation in off-farm work is one such factor. A 1% increase in the percent of household labor working full time off-farm reduces the Gini coefficient by 0.088%. Education also contributes to the alleviation of income inequality. One more year of schooling of household head lowers income inequality by 0.429%. In contrast, a higher degree of land fragmentation and a higher share of saline soil both increase income inequality. This is expected because poor and disadvantaged farmers have fewer ways to avoid or alleviate the damages caused by environment deterioration. Thus, they suffer more from the damages than rich farmers.

5. Conclusion

The analysis in this paper shows that tubewell irrigation, either in the form of sinking own tubewells or purchasing water from tubewell owners, has a positive impact on both crop income and total income of farmers in Pakistan. Tubewell irrigation also works to alleviate income inequality in rural Pakistan. So at least in our sample area, the spread of tubewells and the development of groundwater markets have a positive effect on income distribution. Our findings say that policy makers should be supportive of tubewell irrigation. In particular, our results show that area irrigated by purchased groundwater has a much stronger effect on equalizing income distribution than area irrigated by own groundwater. This suggests that policy efforts should focus more on the development of groundwater markets, not on installing more tubewells. Policies such as subsidies for farmers to purchase plastic pipes to deliver groundwater to their fields or laying underground pipes are all candidates. Obstacles for developing water markets should be remove or minimize. Policy makers can also use other tools to reduce income inequality. For example, policies providing more equal opportunities for farmers to work off-farm and enhance household off-farm income will improve the income distribution, because the poor and disadvantaged groups benefit more from participation in off-farm employment. Policies that improve education level will have large impacts on equalizing income too. Reducing land fragmentation and soil salinity are other aspects policy makers can look at to help equalizing income distribution.

Our policy recommendation, however, does not mean that tubewell irrigation should be increased at any cost. Although our cross-sectional study shows the positive effects of tubewell irrigation at least in the short term, we are not saying that the government should leave the complete control of groundwater to farmers. The development of tubewell irrigation should take into considerations of the long term effect. One potential effect is declining water tables. In our sample, at the time when the tubewells were drilled (mostly between 1992 and 2010), the average depth to water in wells was 54 feet. In 2011, the average depth to water in wells rose to 65 feet. If this trend continues, the higher pumping costs will eventually wipe out the benefits. In India, the spread of private tubewell construction and large subsidies on electricity in agricultural sector have been found to worsen water scarcity problem in many semi-arid and arid regions (Bassi, 2014). The excessive pumping and the consequent depletion of groundwater resources may exacerbate income inequality, because poorer farmers have less resource to fall back on if groundwater is depleted to a level that is not economically usable anymore.

Although there are very few studies on the long term impact of groundwater markets on income inequality, a few studies on schemes that are similar to groundwater markets shed some lights on this. Theoretical analysis in Msangi and Howitt (2007) employs a dynamic optimization framework to analyze groundwater extraction over time and find that market-based instruments such as tradable pumping quotas could achieve both higher efficiency and lower income inequality. Bourgeon et al. (2008) also construct a theoretical model to analyze the effect of water trading. They assumed a small rural economy where rural agents earn income from irrigated agriculture sector, nonagricultural sector and water trade. Water rights are tied to land ownership. Their results show that if there were no job-search cost, per capita regional welfare would enhanced with increased water trading. However, at least one group of regional agents, i.e. farmers or service providers, would be hurt by water trading. Giannoccaro et al. (2010) find that under a moderate level of water price, water rights quota has a positive effect on the income distribution among different social groups such as landowners, capitalists and especially temporary workers. Intuitively, the positive effect of water trading on income distribution may be because participation in water trading is voluntary and poor farmers would only enter the transaction when it is beneficial for them to do so.

Another potential long-term effect is the deterioration of water quality. The survey shows that the EC level of groundwater has increased from 1570 mmhos/cm in 2002 to 2792 mmhos/cm in 2012. The rise in salinity may be due to the decline in the quantity of groundwater (because more groundwater is used in irrigation) combined with the increase in the amount of salt in the soil (salt accumulation due to excessive leaching in groundwater irrigation). If salinity exceeds some threshold, crop yields could be reduced to zero (Haman, 2000). Such a trend in the deterioration of water quality threatens the sustainability of agricultural growth and the health of the ecosystem. Programs that encourage the development of groundwater irrigation should be designed in a way that balances the benefits in the short term and the long term so that groundwater resources can support the sustainable growth of agriculture. Studies that evaluate the cost-effectiveness of these programs should be encouraged to see if each dollar spent results in aggregate gains greater than one dollar. Governments should also put in more efforts to monitor the changes in both the quantity and the quality of groundwater resources, particularly in areas where groundwater is being severely depleted. Other policy instruments, such as the removal of subsidies on electricity and diesel prices, should also be considered so that the scarcity value of groundwater resources can be taken into account. Moreover, under the flat-rate system of energy pricing, most of the energy subsidies have gone to a small fraction of farmers while the majority of small farmers and farmers without any irrigated crop land receive much less benefit (Vashishtha and Gupta, 2006; Howes and Murgai, 2003). This worsens income inequality among farmers. A proper scheme of energy pricing could ensure higher efficiency and equity of water use among farmers and take account of sustainability of groundwater resources in rural area. Establishing private and tradable water right, and charging pro rate for energy use in the farm sector improve efficiency of groundwater use and alleviate over-extraction problem (Kumar et al., 2011; Bassi, 2014). Pro rate energy pricing and higher power tariff are also social-economically feasible for small farmers, combined with advanced technologies for metering electricity consumption that can lower the transaction cost (Kumar et al., 2013). It should also be noted that canal irrigation still plays an important role in tubewell irrigated area. Therefore, the development of groundwater markets should not be a reason for the government not to attempt to improve the quality of irrigation services from the public canal network. Our result that tubewell irrigation increases the income of groundwater users (relative to canal-only users) is most likely due to the unreliability of canal water. In general, farmers prefer canal water (Ahmad et al., 2007). So government should work to increase canal water supply to farmers.

The main limitation of our study is that we do not have a set of panel data or time series data at hand to evaluate the long term impact of private tubewell irrigation. Lack of data is also the reason that we do not see a large literature on the groundwater economy in rural Pakistan. Continuing to collect household level data over time so that researchers have access to panel data will improve the quality of quantitative analysis. Estimation methods such as household fixed effects can be used to address the endogeneity problem. Panel data are also needed to enable researchers to reassess the effect of tubewell as the landscape in Pakistan's agriculture changes.

Appendix A. Method of Gini decomposition

The decomposition starts with a measure of the Gini coefficient, A, which is half of Gini's mean difference (Lerman and Yitzhaki, 1985). Higher values of A indicate more unequally distributed income. A is defined as:

$$A = \int_a^b F(y)(1 - F(y))dy, \tag{A1}$$

where y is income, a is the lower bound o income, b is the upper bound o income, and F is the cumulative distribution of income. Using integration by parts and rules of calculating probabilities, A can be written as follows:

$$A = 2cov(y, F(y)). \tag{A2}$$

The steps to derive A are as follows. Define $f(y)$ as the probability density function of y, and use integration by parts, we have:

$$\begin{aligned} A &= yF(y)(1 - F(y))|_b^a - \int_a^b y(f(y) - 2F(y)f(y))dy \\ &= 2\int_a^b y(F(y) - 0.5)dF(y). \end{aligned} \tag{A3}$$

Define $G(x)$ as the cumulative density function of F, $g(x)$ as the probability density function of F. Therefore, we know that:

$$\begin{aligned} g(x) &= \frac{\partial G(x)}{\partial x} = \frac{\partial \int_a^{F^{-1}(x)} f(y)dy}{\partial x} = f(F^{-1}(x)) * \frac{\partial F^{-1}(x)}{\partial x} \\ &= f(F^{-1}(x)) * \frac{1}{f(F^{-1}(x))} = 1. \end{aligned} \tag{A4}$$

That is, F is uniformly distributed on $[0,1]$ and its mean is 0.5. Then, A can be written as follows:

$$A = 2\left(\int_a^b yF(y)dF(y) - 0.5\int_a^b ydF(y)\right) = 2(E(yF(y)) - E(F(y))E(y)). \tag{A5}$$

Because

$$cov(y, F(y)) = E(yF(y)) - E(F(y))E(y), \tag{A6}$$

then

$$A = 2cov(y, F(y)). \tag{A7}$$

Therefore, the status of income inequality depends on the relationship between income and its cumulative distribution. Let $y_1, \ldots, y_k$ be the components of y from various sources and so $y = \sum_{k=1}^K y_k$. Then A becomes:

$$A = 2\sum_{k=1}^K cov(y_k, F). \tag{A8}$$

The steps to derive it are as follows.

$$A = 2cov\left(\sum_{k=1}^K y_k, F(y)\right) = 2\left(E\left(\sum_{k=1}^K y_k F(y)\right) - E(F(y))E\left(\sum_{k=1}^K y_k\right)\right). \tag{A9}$$

Since

$$E\left(\sum_{k=1}^K y_k F(y)\right) = \sum_{k=1}^K E(y_k F(y)),\ \ E\left(F(y)E\left(\sum_{k=1}^K y_k\right)\right) = \sum_{k=1}^K E(F(y))E(y_k), \tag{A10}$$

then

$$A = 2\sum_{k=1}^K E(F(y))E(y_k) - E(F(y))E(y_k) = 2\sum_{k=1}^K cov(y_k, F). \tag{A11}$$

If an income source is positively related to the income distribution, then an increase in that income source will increase the income inequality. If the income source is negatively related to the income distribution, then the income inequality will be reduced with smaller contribution from that income source. Dividing A by the mean income (m) yields the conventional Gini coefficient, G.

$$G = \frac{2\sum_{k=1}^K cov(y_k, F)}{m} = \sum_{k=1}^K \frac{cov(y_k, F)}{cov(y_k, F_k)} * \frac{2cov(y_k, F_k)}{m_k} * \frac{m_k}{m}, \tag{A12}$$

$$G = \sum_{k=1}^K R_k G_k S_k,$$

where $R_k = \frac{cov(y_k, F)}{cov(y_k, F_k)}$ is the Gini correlation between income source k and total income, $G_k = \frac{2cov(y_k, F_k)}{m_k}$ is the relative Gini of income from source k and $S_k = \frac{m_k}{m}$ is the share of source k in total income. Consider a small exogenous change in income from source k by a factor e_k, such that $m_k(e_k) = (1 + e_k)m_k$. Then Stark et al. (1986) show that the partial derivatives of the Gini coefficient with respect to a percent change e_k in source k is

$$\frac{\partial G}{\partial e_k} = S_k(G_k R_k - G). \tag{A13}$$

Therefore, the source's marginal effect relative to the overall Gini can be written as follows:

$$\frac{\partial G/\partial e_k}{G} = \frac{S_k G_k R_k}{G} - S_k. \tag{A14}$$

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