



Towards Sustainable Water Use: Factors Influencing Farmers' Participation in the Informal Groundwater Markets in Pakistan

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Informal groundwater markets have spontaneously developed in Pakistan due to the heterogeneity of farmers' resource endowments, irrigation water shortages, and productivity gains of groundwater. Evidence shows that water allocation through formal or informal water markets can result in significant benefits for buyers and sellers and improve sustainable water use. Existing literature on water markets generally takes only buyers' perspectives into account when studying the factors influencing the purchase of groundwater for irrigation. In contrast, we look at the perspectives of both buyers and sellers to investigate farmers' participation in informal water markets. We conducted this study in the three agroecological zones of Punjab. The data was collected from a sample size of 360 farmers, with an equal proportion of water buyers, sellers, and self-users. Cragg's double hurdle model was used to investigate the factors influencing the extent of water buying or selling. Results of the demand side analysis show that educated has negative correlation with water market participation and level of water purchasing. In addition, large farmers are less likely to buy water, indicating that the majority of farmers in water markets are smallholders. However, the degree of land fragmentation, soil fertility, and adoption of improved seeds each have may increase water market participation. Water cost and farmers' family size has negative impact on level of water purchasing. The results of supply side analysis show that tubewell capacity, degree of land fragmentation, and the number of operational tubewells at a given farm have a positive relationship with the likelihood of selling water. When it comes to the amount of water sold, two factors that positively influence the extent of water selling are the income from water sales and the degree of land fragmentation. Finally, we discuss the implications of these results for sustainable water extraction in the water markets.

Keywords: sustainable water extraction, groundwater trading, farmer participation, groundwater governance, environmental externalities, groundwater markets, Pakistan

1 INTRODUCTION

Water markets are an economic tool for allocating scarce water resources productively, particularly for agricultural purposes (Tsur, 2005). A water market is defined as a set of institutional mechanisms that enable the purchase and sale of water rights (for extraction and use) (Theesfeld, 2010). Water markets exist in various forms in many countries around the world. These can be formal or informal, coordinated or spontaneous. Their members (or participants) may exchange water rights or water at a fixed price paid on the spot or for future quantities of water (Tsur and Dinar, 1997). Because the specific conditions for exchanging water in water markets vary greatly between countries, the nomenclature varies. If water rights are the subject of the exchange, this is referred to as a market for water rights or a market for water licenses in the literature. The term “leasing” refers to water markets in which long-term access to water is traded between various entities. If the trading of water is related to water allocation, it is simply referred to as water allocation (as in Australia) or water assignment (e.g., in Canada). These examples above are typically related to more formal water markets. Water is allocated informally in informal water markets through short-term and localized trades between agents (buyers and sellers) (Brewer et al., 2008; Giannoccaro et al., 2013). This terminology is more applicable to our scenario in this paper. While formal water markets are more prevalent in developed countries such as Australia and the western United States (with Chile being an important exception), informal water markets are found throughout Asia (Hadjigeorgalis, 2008b).

Evidence from various countries shows that water allocation through formal or informal water markets can result in significant benefits for buyers and sellers, and these benefits are especially pronounced during times of water scarcity (Connell and Grafton, 2011). Furthermore, water trading through informal water markets can improve small and marginal farmers’ access to water and increase their agricultural income (Manjunatha A. et al., 2011; Saleth, 2014; Manjunatha et al., 2016). Water markets have the potential to cope with climate change, but the consequences are unknown (Wei et al., 2011; Kiem, 2013). Furthermore, water markets can also enhance sustainable water use and remove environmental externalities as they divert water to the most efficient use. Studies show that, for a water market to function properly, there must be sufficient heterogeneity among different water users (Schoengold and Zilberman, 2007). The skewed distribution of water pumping rights or users’ ability to extract groundwater—a feature particularly relevant to informal water markets—can also be beneficial in the development of water markets (Garrido and Livingston, 2003). When conditions are favorable, informal water markets have a positive impact on water sustainability, equity, and efficiency. However, these effects are mitigated by the threat of water scarcity (Mukherji, 2007). Overextraction in the absence of groundwater management can lead to land subsidence, saltwater intrusion, and aquifer drawdown (Chen et al., 2003; Knapp et al., 2003; Wang et al., 2007). While these phenomena are not unique to water markets, the substitution of pumped groundwater for surface water sales can exacerbate them

(Hadjigeorgalis, 2008a). Therefore (Grafton et al., 2011), argue that water markets should be evaluated based on the context and relevance of factors such as economic efficiency, equity, and environmental sustainability in a specific area.

While externalities are a common problem in water markets, they are not without a solution. Externalities, whether they affect the environment or other users, can be factored into market prices to offset the social costs associated with market transactions (Hadjigeorgalis, 2009). Furthermore, these impacts vary from region to region and depend upon the regulations and degree to which markets are efficient. In some cases, the informal water markets may contribute to the sustainability of water. It is pertinent because of two reasons. First, efficient water markets provide incentives for conservation and may reduce water withdrawals. Second, an efficient water market can reduce the incentive for the installation of tubewell by every farmer, thus reducing overdraft of water. Similarly, Hardin (1972) argues that responsible water users benefit from the water market as it provides an incentive for civil behavior by water users and those who want to protect the environment. However, Saleth (2014) points out that in the absence of an institutional and legal framework that imposes limits on water withdrawals, the water markets cannot ensure the sustainable use of water. Water markets promote water efficiency as long as third-party impacts are fully considered (Bauer (2013).

To ensure the efficient allocation of scarce water resources in agriculture, policymakers and governments must understand the factors that encourage (or discourage) farmers’ participation in water markets (Wheeler et al., 2009). Groundwater management is especially challenging in developing countries. A better understanding of existing groundwater markets can lead to the improved institutional design of such water markets. Understanding why farmers choose to participate in informal water markets can also shed light on why some rules may be more effective in one market than another.

The groundwater markets are active in all provinces of Pakistan, with the highest concentration in Punjab province, which has seen the most groundwater development (Razzaq et al., 2019; Razzaq et al., 2022a). Almost one-third of Punjab’s private tubewell owners sell water from their pumps (Qureshi et al., 2003). These groundwater markets are informal since they are not governed by formal rules. In contrast to developed countries, groundwater property rights in informal water markets are not well-defined. Any farmer is free to buy and sell as much water as they want. Aside from water prices, physical conditions and social relationships influence the water trading system. While most large farmers in Punjab have tubewells, poor farmers must buy water for irrigation. However, due to the lowering of water tables, many tubewell owners are now forced to participate in groundwater market processes to buy water because a single tube well cannot satisfy their irrigation needs (Razzaq et al., 2019). Furthermore, recent evidence also indicates that groundwater markets improve farmland utilization, farmer income, and equity of water access in Punjab province (Razzaq et al., 2022b).

In this paper, we attempt to understand farmers’ decisions to participate in groundwater markets in Punjab, Pakistan, i.e., why

and under what conditions farmers choose to buy and sell farmers, as well as why some farmers do not participate in water markets. Previous research on farmers' participation in groundwater markets has been conducted in a number of Asian countries, including Rajasthan, India (Sharma and Sharma, 2006) in which authors investigated the factors influencing farmers' decision to purchase water. In another study (Manjunatha et al., 2014), looked at farmers' participation in the water-stressed Eastern Dry zone of Karnataka and discovered that agricultural credit and failed wells increase the likelihood of buying water. It is because of misuse of agricultural credit (Elahi et al., 2018). Jaghdani and Brümmer (2015) examined the factors of water purchase by Iranian pistachio farmers and identified that technological variables influence farmers' participation decisions. Many researchers have also investigated the factors influencing farmers' willingness to trade water in developed countries such as Australia (Wheeler et al., 2012), Spain (Giannoccaro et al., 2013; Giannoccaro et al., 2015), and the USA (Cook and Rabotyagov, 2014). Farmers willing to adopt technology is dependent on various external and internal factors (Elahi et al., 2021b; Elahi et al., 2022a). Overall, previous research indicates that farmers' socioeconomic characteristics play a significant role in their decision to participate in water markets. The relevant literature on informal water markets, however, generally takes buyers' perspectives into account when studying the factors influencing the purchase of groundwater for irrigation. Considering the research gaps, we look at the perspectives of both buyers and sellers to investigate farmers' participation in informal water markets. In addition, we use the Cragg's double hurdle model to investigate the factors influencing the extent of water buying or selling. Furthermore, previous studies are generally limited in scale and do not take spatial factors into account. We conduct this study in the three agroecological zones of Punjab to investigate the farmers decision to buy and sell water.

The remainder of the paper is structured as follows. The following section describes the study area, sampling frame, and data collection, as well as the empirical model used to investigate factors influencing farmers' participation and the extent of water selling. The descriptive statistics and empirical findings of the study are then described. Finally, the last section concludes the study's findings and provides policy implications.

2 MATERIALS AND METHODS

2.1 The Sampling Frame and Data Collection

Data on groundwater markets was collected from the province of Punjab. Our selection of this province was based on its high groundwater trading and intensive use of groundwater for agriculture. It is estimated that about 76% of the land in the province is irrigated with groundwater. By comparison, the province accounts for a majority of the agricultural income of the country. In addition, 63% of the country's total agricultural area is in Punjab province (Naseer et al., 2016). Due to fluctuations in surface water provided by canal network,

farmers in some areas entirely depend on groundwater irrigation (Imran et al., 2018; Razzaq et al., 2018; Naseer et al., 2020).

Additionally, the province has seen massive growth in the installation of tubewells in the past four decades. Farming in the province is mostly a subsistence type by small farmers who rear dairy animals for money, grow crops or practice mixed farming (Ashfaq et al., 2015a; Ashfaq et al., 2015b). There is a low rate of entrepreneurship in the province (Aamir et al., 2021b). In fact, 63 percent of farms in the province are owned by small farmers. Most of these farms are less than 5 acres in size (Naseer et al., 2016; Naseer et al., 2019). Many these small farmers are not able to install tubewells due to financial constraints since it requires significant investment. Consequently, these farmers depend on groundwater irrigation. Additionally, drip irrigation and other water conservation technologies are not widely used in the province, which leads to a high usage of water. Small farmers are compelled to purchase water, resulting in a groundwater market (Razzaq et al., 2018). In the province, the area equipped for irrigation (AEI) is very high, as illustrated by **Figure 1**.

Following (Elahi et al., 2021a; Elahi et al., 2022b), a multi-stage sampling technique was used to select the sample size from 12 villages in three districts in the Punjab province, namely Gujrat, Sahiwal, and Sargodha (**Figure 1**). In the first stage of sampling, three districts were chosen from each of Punjab's three main agro-ecological zones to incorporate spatial features in the analysis for a more in-depth understanding of the dynamics of groundwater markets. The Gujrat district is in the rice-wheat zone and is semi-arid; the Sahiwal district is in the mixed cropping zone, and the Sahiwal district is in the cotton-wheat zone. Groundwater is extensively used in all of these districts, causing groundwater levels to fall (Qureshi, 2020). Furthermore, the cropping pattern, farm structures, groundwater development, precipitation rates, and groundwater market activity vary across these districts. These distinctions provide enough heterogeneity in the dataset to capture spatial effects. In the second stage, two tehsils (sub-division) were chosen at random from each district. Then, two blocks (union councils) were chosen at random from each tehsil in the third stage of sample selection. In the fourth stage, one village was chosen at random from each block. As a result, a total of 12 villages were chosen from the three districts. The respondents were chosen using a combination of purposive and random selection procedures in the final stage. For each of the sample villages, we compiled a list of the self-users, buyers, and sellers of water, and then randomly selected 10 farmers from each category, producing a total of 30 farmers (10 buyers, 10 sellers, and 10 self-users) from each village. Following this sampling strategy, a total sample size of 360 farmers was chosen, with an equal proportion of water buyers, sellers, and self-users.

In order to collect data from farmers, we developed a well-structured questionnaire. The interviewer gathered detailed information from farmers involved in water trading and from self-users of water in person and recorded it. Since wheat was found to be cultivated by all farmers, therefore we collected relevant data for wheat production. The questionnaire was designed to obtain information on socioeconomic

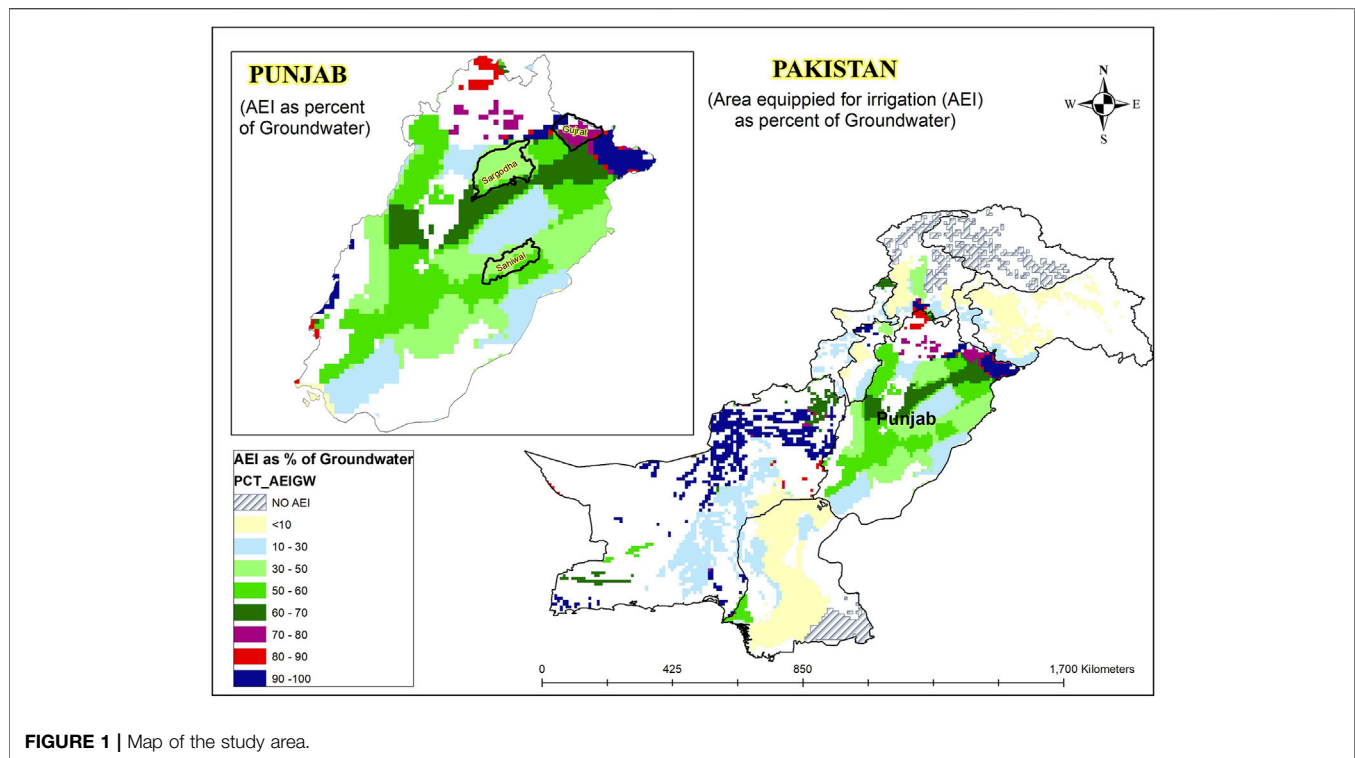


FIGURE 1 | Map of the study area.

characteristics, wheat production technology, detailed information on groundwater use, tubewell ownership and specifications, cost and mechanism of groundwater extraction, the power source of tubewells, contractual arrangements between groundwater users, and water prices. We conducted the survey with the help of trained enumerators. In order to ensure quality of data collection, enumerators were trained on-the-field, and the questionnaire was pre-tested to refine it.

2.2 Analytical Framework

As previously stated, one of the study's distinguishing features is that we not only focus on water purchasing decisions but also incorporate seller characteristics to analyze their water selling decisions. It was important to note that among the self-users were some farmers who owned tubewells but reported insufficient water discharge from their tubewells to meet their irrigation needs. Furthermore, some tubewell owners in this category owned numerous land parcels, and their own wells could not irrigate all of their lands. Despite these reasons, they did not purchase water. These farmers are classified as potential buyers in this study. There were 64 farmers identified as potential buyers due to insufficient groundwater from their tubewells or a greater number of land fragments. Furthermore, some self-user farmers reported having surplus groundwater over their irrigation needs, but they did not sell water. Therefore, we classify these farmers as potential sellers. There were 56 self-users identified as potential sellers. We use data from 120 buyers and 64 potential buyers from our total sample to investigate the factors influencing farmers' water purchasing decisions and the extent of participation. In addition, we used data from 120 sellers and 56 potential sellers to

determine the factors influencing farmers' water selling decisions and the extent to which they participate in groundwater markets. In the remainder of this study, we use the terms "participants" and "non-participants" in groundwater markets for buyers and sellers, and potential buyers and potential sellers, respectively.

2.2.1 Empirical Model

Despite the existence of demand for groundwater, some farmers in this sample participated in land markets for groundwater, while others did not. Furthermore, those who purchased differed in the amount of water they purchased. Similarly, some farmers in the sample sold water at water markets, but others did not, even if they had enough water to sell to others. A variation in the amount of water sold was also seen in the sample. Consequently, we attempt to understand this behavior to answer the following questions: why do some farmers purchase groundwater in groundwater markets while others do not, even when demand exists, and why is the quantity of water purchased different among buyers? Also, what makes some farmers sell water while others don't, despite having surplus water to sell, and to what extent do water sellers sell water?

It is often difficult for analysts to use only one regression model (Aamir et al., 2021a). To analyze factors that affect farmers' participation in water markets and the extent of their buying and selling, Craig's double hurdle model was considered appropriate. If a farmer decides to participate in the water markets, he or she must overcome two obstacles. The decision-maker must first decide whether to participate in the market and then decide how much water to purchase or sell. To put it another way, the second hurdle has to do with how much participation will occur. The

double hurdle model assumes these two decisions are made separately rather than at the same time. This assumption closely resembles the reality observed in informal water markets. It is possible that a farmer will decide to participate in the water market at the start of the season even though his plans are not perfect. Based on this decision, he may cultivate a specific area. Nevertheless, his/her subsequent decision to buy or sell water may be affected by several factors, including the cost of water, the cost of other production inputs, the availability of water, precipitation levels, and the water requirements of various crops.

The two stages of Cragg's model are analyzed differently due to the different nature of the dependent variables. The first stage is a probit model which can be used to analyze the decision maker's decision to participate in the water markets. The second stage of the model is a truncated model that can be used to estimate the level of participation in water markets, in other words, the amount of water purchased or sold (Cragg, 1971). Let's suppose w_i^* is the latent variable that describes farmers participation decision, and y_i^* is the latent variable that describes the farmers' decision on the extent of participation (i.e., quantify of water). In this case, w_i and y_i are the observed counterparts. A farmer's two hurdles in a particular water market, as specified by (Cragg, 1971) and (Moffatt, 2005), are:

$$w_i^* = \alpha z_i + v_i (\text{Participation decision}) \quad (1)$$

$$y_i^* = \beta x_i + \varepsilon_i (\text{Level of participation}) \quad (2)$$

where,

$$w_i = \begin{cases} 1, & \text{if } w_i^* > 0 \\ 0, & \text{if } w_i^* \leq 0 \end{cases}; \text{ and}$$

$$y_i = \begin{cases} y_i^*, & \text{if } y_i > 0 \text{ and } w_i^* > 0 \\ 0, & \text{if otherwise} \end{cases}$$

In Eqs 1, 2, the vector z_i can be thought of as an indicator of the factors affecting farmers' decision to participate in the water market, the vector x_i as an indicator of the extent of participation (water sold or bought), and v_i and ε_i as an indicator of errors.

Since the informal trading groundwater markets can be understood by examining both demand-side and supply-side factors of Eqs 1, 2, therefore two separate models were estimated. Because the dependent variables in the two stages of Eqs 1, 2 differ, the first stage equation in both models is calculated using a probit model whereas the second stage equation is computed using a truncated regression.

2.2.2 Variable Definition and Measurement

Eqs 1, 2 represent the two stages of Cragg's double hurdle model. The dependent variable in the first stage (probit model) of both demand-side and supply-side equations was farmers' participation (1 for participating farmers, and 0 for non-participants). The dependent variable in the second stage (truncated regression) was the extent of participation (i.e., the quantity of water bought or sold).

The independent variables in the demand-side analysis included education of the farmer, farm size, family

size, off-farm income, number of farm fragments, reported soil fertility, adoption of high yielding variety, cost per cubic meter of water, the dummy for failed tubewells, and location dummies.

The explanatory variables used to analyze the supply-side determinants of water market participation and level of participation (i.e., the extent of water sold) included education of the farmer, family size of the farmer, farmers own water use, tubewell capacity, income from selling of water, joint ownership of tubewells, number of farm fragments, number of functioning wells, and cost of water. Data on all these variables were obtained from farmers using a structured survey instrument. The definition and measurement units of these variables is provided in Table 1.

The data on all variables in Table 1 was obtained directly from the farmers. However, the amount of water was estimated indirectly using the information on tubewell specifications obtained from farmers. This information included irrigation duration for the wheat crop, depth of bore, the diameter of the suction pipe, and horsepower of diesel engine, electric motor, or tractor used to operate the tubewell. Following Eyhorn et al. (2005); Srivastava et al. (2009), and Watto and Mugeru (2014), a pre-tested formula was used to estimate the quantity of groundwater applied to wheat crop:

$$Q = \frac{t \times 1295741.1 \times BHP}{d + (255.5998) \times BHP^2} / d^2 \times D^4$$

where, Q is the amount of groundwater extracted (liters), t is the total duration of irrigation (hours), d is the depth of the borehole (meters), BHP is the engine power of the pump (HP), and D is the suction pipe diameter (inches). The amount of water was converted to a cubic meter to be included in the analysis.

3 RESULTS AND DISCUSSION

3.1 Factors Influencing Water Buying and Level of Water Buying

Summary statistics of the variables related to participants (water buyers) and non-participants (potential buyers) used in the econometric analysis of factors affecting water purchases and water purchase levels are shown in Table 2. The socioeconomic indicators show that non-participants have significantly more education and larger landholdings than participants. They also have significantly more non-farm income. The off-farm income variable is included because evidence from Uttar Pradesh and Rajasthan, India (Sharma and Sharma, 2006; Singh and Singh, 2006) show that off-farm income reduces the likelihood of purchasing water. These results indicate that the non-participants have a better socioeconomic status than the participants. Deepak et al. (2005), Sharma and Sharma (2006), and Manjunatha A. V. et al. (2011) report similar findings.

One of the defining features of the farming community in the study regions is the existence of many small farmers with a land size of fewer than 5 acres. In addition, due to inheritance laws and lack of implementation of land consolidation reforms, smallholdings of farmers are further divided into many

TABLE 1 | Definition and measurement of variables used in demand-side and supply-side analysis of water market participation and level of participation.

Variables	Unit	Definition
Education of the farmer	Years	Number of schooling years
Family size	Number	Number of family members of a farming household
Farm size	Acres	Area owned by farm household
Off-farm income	PKR/month	Income received from sources other than farming
Farm fragments	Number	Number of fragmented parcels of land
Cost of water	PKR/m ³	Irrigation cost per m ³
Functioning tubewells	Number	Number of functioning tubewells
Capacity of tubewell	HP	Horsepower of the water extraction mechanism
Income from the selling of water	PKR/year	Income of selling of water in the last year
Own water use	m ³	Amount of water used for irrigation by the seller
Amount of water purchased	m ³ /acre	Amount of tubewell water purchased for irrigation
Duration of water sold	Hours/year	Total duration for which tubewell water is sold in a year
Failed tubewells	Binary	1 if farmer has failed tubewells on the farm, 0 otherwise
Reported soil fertility	Binary	1 if farmer reported soil as fertile, 0 otherwise
Adoption of a high-yielding variety	Binary	1 if a farmer used high yielding wheat variety, 0 otherwise
Joint ownership of tubewell	Binary	1 if tubewell has joint ownership, 0 otherwise
District Gujrat ^a	Binary	1 if a farmer is in district Gujrat, 0 otherwise
District Sahiwal ^a	Binary	1 if a farmer is in district Sahiwal, 0 otherwise

^aDistrict Sargodha is used as the base category for location dummies.

TABLE 2 | Summary statistics of variables used in the econometric model on per farm basis of water buyers.

Variables	Potential buyers	Buyers
	N = 64	N = 120
Dependent variables		
Participation in water market as water buyer (%)	34.79	65.21
Amount of water purchased (m ³ /acre)	-	2656
Explanatory variables		
Education of the farmer (years)	8.25	6.54***
Family size (No.)	8.30	8.08
Farm size (No.)	8.86	2.36***
Off-farm income	19919	11397***
No. of farm fragments	1.41	1.81***
Soil fertility (1 = if soil is fertile)	0.48	0.68***
Adoption of high yielding variety (1 = if farmer adopts high yielding wheat variety)	0.42	0.56**
Cost of water (PKR/m ³)	1.61	2.15***
Dummy for failed tubewells (1 = have failed tubewell)	0.36	0.31
District Gujrat (1 = if district Gujrat)	0.39	0.33
District Sahiwal (1 = if district Sahiwal)	0.34	0.33

The *t*-test was used to find the statistical significance between potential water buyers and water buyers. *, **, and *** indicate significance levels at 10 percent, 5 percent, and 1 percent, respectively.

fragmented parcels (Naseer et al., 2016). Our sample data also show the existence of fragmented landholdings. Interestingly, small farmers (participants) have significantly more fragmented landholdings than non-participants. It was observed in the field that small farmer with fragmented landholdings did not want to install tubewells, as they called it an economically unfeasible choice. The plains of Punjab lie in the Indus basin, which benefits from fertile soils transported by river water flows. However, differences in soil fertility exist due to extensive farming and loss of topsoil. On average, about 68% of participants reported having fertile soil compared to 48 percent of non-participants.

Since wheat is one of Pakistan's major cash and food crops, many farmers want to use the best agronomic practices to obtain

higher yields. However, in the study areas, the adoption of high-yielding varieties or certified wheat seed still appears to be lower. However, about 56% of participants were found to cultivate high-yielding wheat varieties compared to 42% of non-participants. It was observed that farmers usually change the seed after 3–4 years because the certified seed is expensive compared to the use of their own seed from the previous harvest. However, the use of uncertified seeds may make the crop vulnerable to disease at a later stage and result in poor yields. Therefore, while taking planting decisions, it is an important consideration. Perhaps the reason why more participants use certified seed is that they have small landholdings and want to maximize wheat yield to meet their domestic consumption needs as well as generate a surplus.

TABLE 3 | Factors affecting water buying and level of water buying.

Variables	Probit (first stage)	Truncated (second stage)
	Coefficient (S.E.)	Coefficient (S.E.)
Education of the farmer (years)	-1.225** (0.639)	-0.0037* (0.0018)
Family size (No.)	1.005* (0.564)	-0.0035* (0.0021)
Farm size (No.)	-1.304*** (0.320)	0.0042 (0.0099)
Off-farm income	-0.031 (0.022)	-0.0043 (0.0031)
No. of farm fragments	0.033** (0.012)	0.4142 (0.6083)
Soil fertility (1 = if soil is fertile)	1.462*** (0.576)	-0.0089 (0.0160)
Adoption of high yielding variety (1 = if farmer adopts high yielding wheat variety)	0.695** (0.322)	-0.0163 (0.0150)
Cost of water (PKR/m ³)	0.894 (0.579)	-0.0886*** (0.0161)
Dummy for failed tubewells (1 = have failed tubewell)	0.891 (0.797)	0.0808*** (0.0188)
District Gujrat (1 = if district Gujrat)	-1.516 (1.492)	-0.0124 (0.0195)
District Sahiwal (1 = if district Sahiwal)	2.243 (2.113)	0.0227 (0.0191)
Constant	3.640** (1.642)	3.5657*** (0.0580)
LR Chi ² (11)	212.43	
Prob > Chi ²	0.000	0.000
Pseudo R ²	0.89	-
Log Likelihood	-12.66	138.66
Wald Chi ² (11)	-	92.55

Dependent variable in the probit: 1 = Participant in a water market as a water buyer; Dependent variable in the truncated regression: log of the total quantity of water bought by water buyers.

*, **, and *** indicate significance levels at 10 percent, 5 percent, and 1 percent, respectively; the likelihood ratio test is significant at 1 percent level.

The cost of water per unit is significantly higher for participants. The results show that water buyers in the water markets pay higher prices of up to 33% compared to non-participants. These farmers either pay a flat charge per hour of pumping or use fuel-based contracts with the sellers. Such price differentials were also observed in the studies of Shah (1993), Mukherji (2004), Deepak et al. (2005), Nagaraj et al. (2005), Sharma and Sharma (2006), and Mukherji (2004) in India. Non-participants also had a higher proportion of tubewell failures, but the differences were not statistically significant. Participants purchase water from the water markets, whereas non-participants access water from their own sources. District-wise distribution of the sample size shows that about 39% of non-participants belonged to the district of Gujrat, about 34% to the district of Sahiwal, and the remaining 27% to the district of Sargodha. Since there is evidence of regional differences in water prices and water scarcity levels (Singh, 2002; Kajisa and Takeshi, 2005), we have therefore included these variables in the analysis. The distribution of the sample water market participants is equal (33.33%) in all districts. The independent sample *t*-test was used to estimate differences in explanatory variables for both participants and non-participants. Participants and non-participants differ significantly for all variables except the size of family and failed tubewells dummy variable. The dependent variable in the first stage of the econometric model (probit) is participation in the water market as water buyers and shows that there are 34% of non-participants compared to 65% of participants. The dependent variable in the second stage (truncated regression) is the amount of water purchased (m³), indicating that the participants purchased approximately 2656 m³ of water in the water markets.

The results of the econometric analysis of the factors affecting the purchase of water and the amount of the purchase of water are shown in **Table 3**. In the first stage of the Cragg's double hurdle

model, a probit model is used to determine the determinants of water market participation. The determinants of water purchase levels were identified in the second stage using a truncated regression model. The results show that farmers' education has a negative effect in both stages of the model, which means educated farmers are less likely to take part in the water markets, and they purchase water at a lower rate. These findings are consistent with studies carried out in India on informal water markets (Sharma and Sharma, 2006; Singh and Singh, 2006). It may be argued that educated farmers have a greater off-farm income, so they have a lower incentive to devote their time to agriculture. As a result, they also buy less water. Similarly, the non-farm income coefficient is negative but insignificant for both the participation in the water markets and the level of water purchased.

The family size of farmers is positive and significant in the participation equation, but negative and significant for the level of water purchased. It implies that higher probability of farmers with a large family size to participate in the water markets may be because of several reasons. First, there is a large number of disguised laborers in the agriculture of Punjab. Many people in rural areas do not have adequate employment opportunities, so a large family household is more likely to be engaged in farming. They are therefore also more likely to participate in the water markets for the purchase of water if they do not own a tube well. Second, some poor households exchange labor for water, so a large family household is more likely to participate in water markets. Water markets, therefore, contribute directly and indirectly to the generation of employment. These findings are consistent with Singh and Singh, (2006) which reported similar results in the arid and semi-arid regions of Rajasthan, India. The family size coefficient is negative in the second stage of the Cragg's model, which means that households with a large family size are likely to purchase less water. We may argue

that the application of irrigation requires regular monitoring of the water channels as well as field management. As a result, a household with a large family size is expected to have more family labor available for agriculture, so that irrigation water can be effectively applied to their fields, thus lowering the total quantity of water purchased.

The results show that farm size has a negative impact on farmers' participation in water markets. This implies a higher dependence of small and marginal farmers on the water markets. Descriptive statistics of farmers also show that participants have significantly less farm size than non-participants. Having a smaller farm size also indicates that such farmers are likely to have more liquidity and income constraints so that they may not be able to invest in irrigation facilities such as tubewells. Large farms are more likely to profit from such an investment because they have higher water needs. Due to this fact, large farmers buy less water than small and marginal farmers. This finding is consistent with the study of Saleth, 1991, which also found a negative relationship between farm size and water market participation in three Indian states. The author also reported that water sellers were mostly large farmers who owned borewells. Similar findings have been reported on water markets in several other regions (Deepak et al., 2005; Sharma and Sharma, 2006; Manjunatha A. et al., 2011).

Another significant factor contributing to the participation of farmers is the number of fragmented parcels of land. The results show that participation in the water markets is likely to increase the fragmented land holdings of farmers. As discussed in the descriptive statistics, farmers with more fragmented land find it economically infeasible to invest in irrigation infrastructure on every plot of land. So, instead of installing a new tubewell for every small piece of land, these farmers rely on water purchases through the water markets. This result is consistent with the hypothesis put forward by Kolavalli and Chicoine (1989) and the findings of Saleth (1991) in the state of Haryana, India. However (Saleth, 1991), also found a negative coefficient of land fragmentation for water purchasing decisions in Bihar and West Bengal, India arguing that the technical and economic viability of groundwater purchases is negatively affected by excessive fragmentation. In line with our findings (Sharma and Sharma, 2006), also found a significant and positive relationship between land fragmentation and groundwater purchase in the arid and semi-arid regions of Rajasthan, India. In addition (Jaghdani and Brümmer, 2016), also found that pistachio farmers with a higher degree of land fragmentation were more likely to purchase water through spot water markets in Iran. The effect of land fragmentation on the quantity of water purchased is also positive, albeit insignificant.

The soil fertility variable is found to have a positive coefficient in the first stage of the Cragg's model and is significant. The positive coefficient of soil fertility means that farmers with fertile land are more likely to purchase water. This positive relation between soil fertility and participation in the water market has significant implications for the economic return from additional irrigation through groundwater purchases, given the positive relationship between soil fertility and productivity. A similar finding was reported in several states of India in the water

markets study carried out by (Saleth, 1991). Similarly, the coefficient of adoption of high-yielding crop varieties is positive and significant in the participation equation of Cragg's model, indicating that farmers using certified seed at the beginning of the planting season are more likely to purchase water at a later stage. It can be argued that the adoption of improved seeds for agriculture indicates the intention of farmers to maximize their agricultural returns. As irrigation is critical to generating a surplus, farmers adopting high-yield varieties are more likely to participate in the water markets. In the Indian states of Haryana and Punjab (Saleth, 1991), found a similar positive effect of the adoption of high-yielding crop varieties on water purchasing decisions.

One of the significant determinants of the quantity of water purchased is the cost of water as indicated in the second-stage results of Cragg's model. It implies that, as the price of water increases, the quantity of water purchased through the water markets is reduced. This is in line with economic theory, which entails a negative relationship between price (cost) and demand (water buying). Increased water costs mean less profit for farmers, which has a negative impact on the amount of water purchased. This finding is consistent with the results of Manjunatha et al., 2014, which found a similar relationship between the cost of water and the amount of water purchased. However (Saleth, 1991), found a positive but insignificant relationship between the price of water and the purchase of groundwater. The author attributes the insignificance of the relationship to the meager contribution of water to yields, but this is not the case in the study. Groundwater irrigation has played a significant role in crop yields and farmers' income in Punjab (Qureshi, 2020). The dummy variable for failed tubewells is another important determinant of the water purchase level. The results show that farmers with more non-functioning wells are buying more water to meet their irrigation needs. These non-functioning wells represent sunk costs in agriculture and have contributed to an increase in water costs. As a result, water buyers prefer to buy water rather than invest in additional tubewells, because such investments on the same land are risky and huge (Manjunatha et al., 2014). reported similar findings in the water markets of the Eastern Dry Zone of Karnataka, India.

3.2 Factors Affecting Water Selling and the Extent of Water Selling in Water Markets

The descriptive statistics in Table 4 show the variables used in the econometric analysis of factors affecting the sale of water and the level of sale of water. Approximately 68% of the sample farmers sell water to neighboring farmers and the average duration of the water sold per year is 908 h, which indicated the average tubewell utilization factor of 10 in terms of the sale of water. The utilization factor is defined as the number of hours of tubewell operation divided by the total number of hours per year. The utilization factor is affected by several parameters such as tubewell type, agro-climatic zone, crop season, tariff policy, energy prices, and water markets. Previously, the average utilization factor reported for Punjab was 8.76 (Qureshi et al., 2003). Our result, therefore, indicates that the utilization factor has certainly increased over

TABLE 4 | Summary statistics of variables used in the econometric model on per farm basis of water sellers.

Variables	Potential sellers	Sellers
	(N = 56)	(N = 120)
Dependent variables		
Participation in water market as water seller (%)	31.82	68.18
Duration of water sold (hours/year)	-	908 (467)
Explanatory variables		
Education of the farmer (years)	9.29 (3.69)	7.23 (4.15)
Family size (No.)	9.18 (4.57)	8.93 (5.03)
Own water use (m ³)	4117.07 (837.42)	4237.19 (1496.27)
Tubewell capacity (HP)	18.57 (4.57)	21.06 (12.50)
Income from water selling (PKR) ^a	-	92581 (58953)
Joint tubewells (1 = if tubewell is joint, 0 if private)	0.23 (0.43)	0.13 (0.34)
Fragmented parcels (No.)	1.55 (0.57)	1.89 (0.78)
Functioning tubewells (No.)	1.16 (0.37)	1.42 (0.58)
Cost of water (PKR/hour)	227.09 (68.73)	211.38 (97.34)

The figures in parenthesis are the standard deviation; HP, horsepower.

^aThe logarithmic form was used in the econometric model, but the linear form is reported here for easy understanding.

time, even though our statistics are based solely on the duration of the sale of water. In addition, it was noted that most farmers sold water to neighboring farmers only because of physical restrictions on long-distance transport of water.

The socio-economic indicators of participants and non-participants indicate that non-participants are more educated and have a large family size. Participants have more wells in operation and are therefore more involved in water sales activities compared to non-participants. Participants' own water use is also slightly higher than the non-participants'. Considering the quantity of water sold to others and the use of water at their own farms, participants extracted much more water than non-participants. In addition, the results also show that the average participants have a higher tubewell capacity indicated by the horsepower of the engine used to operate the tubes. This is consistent with the results of Singh and Singh (2006) in the state of Uttar Pradesh, India.

The ownership status of tubewells is another factor that may contribute to farmers' water selling decisions as well as the level of water sold. Approximately 23% of non-participants have joint tubewells compared to 13% of participants. It implies that most water market participants own private tubewells, which gives them greater flexibility in their decision to sell water. Furthermore, the descriptive results show that the groundwater market participants have more fragmented land holdings, which may have driven them to sell water because they may have available surplus water that cannot be transported to other land parcels owned by them. For the cost of water, it is observed that participants have lower costs for the extraction of water compared to non-participants. This may indicate that the water markets have motivated participants (sellers) to adopt a more energy-efficient water extraction mechanism as their average tubewell capacity is higher, but the cost of extraction is still lower. The results further show that the participants earn substantial annual income from the sale of water, which amounts to approximately 92581 PKR per year. The differences between the explanatory variables related to participants and non-participants in the water market are significant for education,

joint tubewells, fragmented land holdings, and functioning wells. The differences between the remaining variables, i.e. the size of the family, the own use of water, the capacity of the tubewells, and the cost of water are not significant.

The results of the econometric analysis of factors affecting the decision of farmers to sell water and the level of water sold are presented in **Table 5**. The determinants of participation in the water markets were identified by the probit model (first stage) and the determinants of the duration of the water sold were identified by the truncated regression (second stage) of the Cragg's double hurdle model. The farmer's education was identified as a significant determinant of participation in the water markets as a seller. It has a negative and significant coefficient indicating that farmers who are more educated are less likely to engage in water sales activities. It can be argued that more educated farmers are also likely to have more off-farm income and therefore do not have a high incentive to earn income from the sale of water. This is in line with our previous findings, which show that more educated farmers are also less likely to purchase water. It appears that the same conclusion applies to participation in the water markets as to water sellers.

Farmers' own use of water has a significant negative impact on the duration of the sale of water to other farmers in the water market. This means that farmers with higher irrigation requirements on their own land are selling less water to others as the sellers first want to meet their own irrigation needs. This also means that profits from the sale of water may be lower than the surplus generated by irrigation in their own fields.

Tubewell capacity is a significant determinant of the decision to sell water as well as the quantity of water sold. In both stages of the model, the coefficient of tubewell capacity is positive and significant, indicating that farmers with high capacity tubewells may have surplus water to sell, which motivates them to participate in the water markets and to sell more water. Consequently, a policy aimed at regulating the flow of water traded in the water markets can target the installed capacity of new tubewell in the farmers' fields. This finding is consistent with Singh and Singh (2006) who found a positive relationship

TABLE 5 | Factors affecting water selling and level of water selling.

Variables	Probit (first stage)	Truncated (second stage)
	Coefficient (S.E.)	Coefficient (S.E.)
Education of the farmer (years)	-0.0649** 0.0279	0.0007 (0.0013)
Family size (No.)	-0.0051 (0.0226)	0.0005 (0.0011)
Own water use (m ³)	-0.0001 (0.0001)	-0.0053*** (0.0010)
Tubewell capacity (HP)	0.0525*** (0.0193)	0.0021** (0.0011)
log of income from water selling (PKR)	-	0.6673*** (0.0253)
Joint tubewells (1 = if tubewell is joint, 0 if private)	-0.5431* (0.2954)	0.0188 (0.0161)
Fragmented parcels (No.)	0.3380** (0.1581)	-0.0094 (0.0068)
Functioning tubewells (No.)	0.5070** (0.2459)	0.0189** (0.0099)
Cost of water (PKR/hour)	-0.0050*** (0.0021)	-0.0004*** (0.0001)
Constant	0.4114 (0.6773)	-0.2347* (0.1346)
LR Chi ² (8)	35.63	-
Prob > Chi ²	0.000	0.000
Pseudo R ²	0.162	-
Log Likelihood	-92.27	175.72
Wald Chi ² (11)	-	1105.73

Dependent variable in the probit: 1 = farmer participates in a water market as a water seller; Dependent variable in the truncated regression: log of the total duration of water sold by sellers. *, **, and *** indicate significance levels at 10 percent, 5 percent, and 1 percent, respectively.

between installed capacity and the decision to sell water to farmers.

Water sales income has been identified as a positive and significant determinant of the level of water sales in the water markets. Furthermore, some farmers may find it more profitable to sell water than to use it for their own farms if the land is not fertile. When a farmer uses irrigation to a higher proportion of his or her own land, he or she needs more water for the farm and therefore sells less water on the market. This result is consistent with Manjunatha et al. (2014), which found a positive effect of water sales revenues on the level of water sold in India.

The ownership status of tubewell is also found to be a significant determinant of participation as a seller in the water markets. The results show that farmers with joint tubewells are less likely to participate in the water markets, indicating that most of the participants own private tubewells. It can be argued that when farmers have joint tubewells, the decision to sell water to neighboring farmers may not be easy, given that farmers also sell water based on social relations. So, all partners in a joint tubewell arrangement may not be willing to sell water to a particular buyer, so there is no sale. Second, there is already a higher pressure on the joint tubewells, as several partners are waiting for their turn to use the tubewell for irrigation. On the other hand, a farmer with a private tubewell is more likely to have excess water and more freedom to make a sale decision. Furthermore, unlike the joint tubewells, the private owner does not have to share the income from the sale of water. This finding is in contrast to the findings of Singh and Singh (2006) which found that joint tubewell had a positive effect on water sales decisions in India.

The variable of fragmented land parcels showed a positive and significant coefficient that means that a farmer with more fragmented land is more likely to sell water than a farmer with more consolidated landholdings. This effect is due to physical restrictions on the transport of water over long distances, as most of the water channels in the study area are

not lined and the adoption of efficiency-enhancing water conveyance equipment among farmers is low. In this situation, the cost of irrigation may rise significantly if remote farms are to be irrigated. So, if a farmer has fragmented land holdings but has a higher tubewell capacity, he or she is better off by selling surplus water to the neighbors. On the other hand, farmers who have consolidated land find it easier to irrigate most of their land because they can make mud channels or even line the watercourses if they have land rights. These results suggest that a land reform policy focusing on land consolidation is likely to increase the efficiency of water use. Previously, Singh and Singh, (2006) and Manjunatha et al. (2014) have identified the positive effect of land fragmentation on water-selling farmers in India.

The results also show that the number of functioning wells is a positive and significant determinant of the decision of farmers to sell water as well as the duration of the sale of water. This result is in line with our hypothesis that farmers with more functioning wells are more likely to have surplus water, thus participating in the water markets and selling more water. In addition, the per hour cost of water has shown a negative impact on the decision to sell water as well as on the level of water sold. This is perhaps due to the fact that the rising cost of water reduces the profit margins of the sellers, as water buyers are small and marginal farmers who cannot afford to pay higher water prices. In addition, water demand is expected to decrease with rising water costs, and therefore the level of water sold is also expected to decrease. In the unique socio-cultural setup of the province of Punjab, the charging of excessive water prices does not reflect well on the social status of the tubewell owners. Consequently, they cannot frequently increase the price because people believe that water is a shared commodity and should not be used to make excessive profits. As a result, the rising cost of extraction reduces the incentive for farmers to sell water as well as the quantity of water sold.

4 CONCLUSIONS AND POLICY IMPLICATIONS

This study used Cragg's double hurdle model to analyze factors that influence farmers' decisions to purchase and sell water and their level of participation in water markets using farm-level data. The results of demand-side analysis of water market participation show that educated farmers are less likely to participate in the water markets and purchase less water. Thus, these farmers have less demand for irrigation water. Farmers with a large family size are more likely to participate in the water markets, but they purchase less amount of water due to surplus labor available for monitoring irrigation applications. Furthermore, we find that large farmers are less likely to purchase water, indicating that most of the participants in water markets are small farmers. Since small farmers make up most of the farming community in rural Punjab, therefore, policies related to the water markets should consider implications of such policies for the subsistence farming community which may be more vulnerable to any changes caused by the policies aimed at governing the conduct of the water markets.

We find that the probability of water purchases increases with an increase in the degree of land fragmentation. Therefore, reforms aimed at land consolidation appear to be an appropriate policy tool for governing the conduct of water markets. It is also found that the probability of water purchases increases when farmers have fertile soil and use improved seeds, which implies that returns from irrigation are higher for farmers who use better agronomic practices. This can be an important message for the agricultural extension department to guide these farmers to improve their productivity. In our results, water prices have depicted a negative impact on the quantity of water purchased, indicating that small farmers are sensitive to fluctuations in water prices. Since water prices are linked to energy costs, therefore, energy tariff policies should consider the welfare effects of such policies on small farmers in the water markets. Finally, the estimated results show that the increase in the number of failed tubewells increases the quantity of water purchased in the water markets.

On the supply side, the estimated results show that educated farmers are less motivated to sell water, most likely because they can earn more off-farm income, and the time spent monitoring water sold for irrigation is worth less than the income generated by off-farm activities. Farmers who use more irrigation water on their own farms sell less water than others, indicating that the returns from water sales are lower than the returns from irrigation on their own farms. Furthermore, the installed tubewell capacity has a positive effect on both the probability and amount of water sold. As a result, controlling the installed capacity of new tubewells through relevant legislation can be an effective tool for better water resource governance and market conduct.

The findings also show that, while farmers sell more water when they make more income from water sales, the cost of

water has a negative impact on their participation and the level of participation in water markets. This implies that the rise in energy prices is not proportional to the rise in water prices charged to small and marginal farmers (buyers). Given this situation, the increase in water costs appears to be reducing water sellers' profits, which has a negative impact on water market participation and may have significant implications for the sustainability, as well as equity of water access for small farmers. This aspect should thus be considered in the context of proposed agricultural differential energy tariff policies, as well as water pricing policies. It is also found that private tubewell owners are more likely to sell water than joint tubewell owners, implying that the ownership status of tubewell influences both water market participation and the level of water sold in a specific area. Moreover, as with demand-side results, the degree of land fragmentation has a positive effect on sellers' participation in water markets. Again, this result implies that land consolidation through reforms is expected to reduce both demand and supply in water markets. Finally, the findings show that farmers with more functional tubewells are more likely to participate in water markets, and the amount of water sold increases as the number of functional tubewells increases. Buyers in the study area pay higher water prices, implying that an effective pricing policy for agricultural water is required. Another option would be to encourage joint investment in irrigation to address equity concerns and the negative externalities of overdrafts while also ensuring resource efficiency.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding authors.

ETHICS STATEMENT

Ethics review and approval/written informed consent was not required as per local legislation and institutional requirements.

AUTHOR CONTRIBUTIONS

AR: Conceptualization, Formal analysis, Investigation, Methodology, Writing—original draft. MX: Data curation, Software, Visualization, Validation, Writing—review and editing. YZ: Investigation, Methodology, Resources, Writing—review and editing. MA: Investigation, Methodology, Resources, Writing—review and editing. HL: Methodology, Resources, Validation, Writing—review and editing. FL: Visualization, Validation, Writing—review and editing.

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