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Impact of Participation in Groundwater Market on Farmland, Income, and Water Access: Evidence from Pakistan

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Abstract: Groundwater irrigation has a critical role in the sustainability of arable farming in many developing countries including Pakistan. Groundwater irrigation is generally practiced to supplement surface water supplies in Pakistan. Nevertheless, uninterrupted and extensive use of groundwater irrigation has raised several concerns about its sustainability and resultant environmental implications. Due to the scarcity of groundwater and heterogeneity in farmers' resources, informal groundwater markets have emerged in Pakistan, where farmers trade water using a contractual system. Yet, the effects of these markets on agricultural productivity and equity remain largely unknown. This paper aims to analyze the impact of participation in the groundwater market on farmland utilization, cropping patterns, water access, and income. We analyze these impacts using primary data collected from 360 farmers in three different zones of the country's largest province. The farmers were categorized as buyers, sellers, and self-users of water. Results indicate that participation in water markets increased agricultural land utilization, evinced by a higher cropping intensity among participants. A horizontal and vertical equity analysis of water markets shows that although large farmers have better access to groundwater irrigation, water market participation improves equity to water access. Based on income inequality measures such as the Gini coefficient and the Lorenz curve, water market participation also improves farmer incomes regardless of farm size. Propensity score matching revealed that wheat yield and income among water-market participants went up by approximately 150 kg and PKR 4503 per acre compared with non-participants. Groundwater market participants' higher crop productivity and income level suggest that water markets need a thorough revisit in terms of policy focus and institutional support to ensure sustainable rural development.

Keywords: water extraction; income inequality; water productivity; land use; sustainability

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1. Introduction

Agriculture is an important source of livelihood for millions of people in South Asia, including Pakistan. Pakistan's economy heavily relies on agriculture despite an increasing contribution by the industrial and services sectors. It is still the largest employer of the rural labor force, and as such, the livelihood of the majority of the population directly or indirectly depends on it. Currently, almost 39% of the population of Pakistan receives employment from this sector. Agricultural production in the country is substantially complemented through groundwater in addition to a well-established canal irrigation system. Over the past few decades, the agricultural production and livelihoods of rural communities in Pakistan have significantly improved due to improved access to groundwater irrigation.

This conclusion is generally valid for other South Asian countries too. For instance, the area equipped for irrigation in South Asia has tripled since 1950 [1] and agricultural productivity has increased manifold. Currently, India, Pakistan, and Bangladesh are the largest groundwater users in the South Asian region. About 85% of groundwater in these countries is mainly used for agriculture, compared to 40% in the rest of the world [2,3]. Consequently, these three countries have 42% of the global groundwater-fed cropland [4]. The major factors behind the heavy utilization of groundwater in agriculture include diminishing surface water supplies and the desire to produce more food for increasing populations in the region [5]. On a micro-level, farmers desire to use groundwater because it provides greater flexibility and better control over the amount and timing of water application, which translates into reduced production risks and improved crop yields. This groundwater "irrigation surplus" enjoyed by farmers is directly related to the quality of irrigation service [6]. However, studies have shown that the prolonged use of groundwater in Pakistan has raised many concerns about the sustainability of this vital resource. For instance, using scenario analysis and assuming the persistence of current dry conditions, Khan et al. [7] find that the groundwater levels in Northeast Pakistan may decline by 10–20 m in the next 25 years. Specifically, due to the overexploitation of groundwater for irrigation, the groundwater level decline was found to be greater in the region where agriculture is more intense [8]. In addition, the highest groundwater depletion rates are being observed in Northeast Pakistan and Northwest India, making them the top hot spots of groundwater depletion in the world [9].

Although it is widely used in agriculture, groundwater irrigation is not equally accessible to all farmers in Pakistan. This is because groundwater pumping for irrigation requires an initial investment in tube well installation, which not every farmer can afford. In particular, the distribution of irrigation control afforded to farmers remains skewed because of the heterogeneity of their resources [10]. Previous research showed that the amount of irrigated land owned per adult equivalent is the most important factor that determines the level of income inequality in rural Pakistan [11]. In the current climate of declining groundwater levels and higher energy costs for pumping groundwater, even for tube well owners, the costs of groundwater irrigation are increasing [5]. The scarcity of groundwater and the increasing demand for irrigation water by all farmers have led to the spontaneous emergence of informal groundwater markets in which groundwater is traded between farmers. At present, these water markets are active in all provinces of Pakistan, with Punjab being the largest agricultural producer and ranking first in such groundwater trading [12].

There is evidence that informal groundwater markets positively increase agricultural productivity and enhance equity among farmers. Most of the literature on the impacts of informal groundwater markets on productivity and equity originates from India. For instance, Singh and Singh [13] found that groundwater markets in Western Uttar Pradesh benefit the participants (buyers and sellers), with small and marginal farmers gaining more from the trade. The authors concluded that farmers should be educated about efficient water extraction devices. Kajisa and Takeshi [14] examined the efficiency and equity of groundwater markets in Madhya Pradesh, India, and found that output-sharing buyers pay higher water prices to sellers than do farmers under other types of contracts. So, inequities exist which depend upon the type of contracts between buyers and sellers. Khanna [15] estimated inequities in production and income for different farmers under various water market regimes in a North Indian village. This study found that water use efficiency was highest on plots irrigated by private tube wells, followed by plots serviced by joint tube wells, and lowest on plots owned by water buyers. In terms of equity and crop productivity, Srivastava et al. [16] found that groundwater markets increase water access and crop water productivity of small farmers in the Central Plain Zone of Uttar Pradesh, India. Furthermore, the authors found that the availability of groundwater had caused farmers to switch to more water-intensive crops, which led to the depletion of groundwater.

The literature on the productivity and equity impacts of groundwater markets in Pakistan is limited. The most important study conducted on this issue was based on an IFPRI micro-survey of 1991–1992 in two districts of Pakistan (only one from Punjab). Based on this survey data, Mainzen-Dick [12] found that purchased tube well water was not as productive as the water from their own tube wells. In addition, groundwater markets were found to positively impact equity as they give small farmers better access to water. However, this study was based on a micro dataset that included only 16 tube wells in the sample, for which the data were collected about 30 years ago. Since then, the dynamics of groundwater use have significantly changed due to improvements in water extraction technologies and increasing water scarcity. Additionally, since then the groundwater tables in Punjab have been significantly depleted, and groundwater irrigation costs have sharply increased. Numerous tube wells have run dry, and farmers are struggling to install new tube wells. These declining water tables are not only making groundwater irrigation expensive but also unreliable [5]. Furthermore, recent studies showed mixed results in the productivity and equity impacts of groundwater markets. For instance, Wang et al. [17] examined the effect of private tube wells on rural income levels and income distribution in Pakistan; their results showed that private tube wells have a positive effect on enhancing rural income and reducing income inequality. However, if monopolistic tube well owners force farmers to pay much higher water prices, groundwater markets may reinforce the disparity between tube well owners and non-owners [18]. So, the question arises as to whether the equity and productivity impacts of groundwater markets are still relevant and economically justifiable, and what policies should be implemented to correct the course of informal groundwater markets to improve groundwater governance in Pakistan, especially in the Punjab province, which is the largest groundwater user. Considering this background, we aim to study the informal groundwater markets with a spatially versatile dataset to comprehensively understand their productivity and equity impacts and suggest appropriate policy measures in the context of the growing groundwater scarcity in the Punjab province of Pakistan.

Theoretical Background

The need for optimal water allocation gave rise to the idea of water markets. Socially optimal water allocation maximizes a region's net production, and it is often thought of as a benevolent social planner's optimum choice. If the allocation of resources (including compensating transfers of money) is such that no one can be made better off without making anyone else worse off, the social optimum is called the Pareto efficient in economics [19]. A situation in which all welfare-enhancing trades and technological choices are implemented is another way of conceptualizing the social optimum. The main economic consequence of such allocation is that the marginal prices of water are equalized for all uses [20]. In the water markets context, this social optimum is referred to as "efficient" by economists because water is distributed to those who value it the most [21]. Early advocates of water reallocations identified water transfers from low-valued agriculture to high-valued municipal and industrial uses as socially optimal based on this definition [22,23]. Water transfer from low-value to high-value uses in agriculture was also suggested as a way to improve optimal allocation [24].

Owing to the failure of governments in developing countries to respond to rapidly changing water demands, informal water markets have emerged to manage water scarcity. Although the water trade in these markets is technically illegal, they are politically popular and manage to reallocate water quickly and voluntarily. Therefore, the government usually turns a blind eye to these informal water markets [25–27]. Water rights in these informal water markets such as those found in India and Pakistan already exist in some form. These rights are usufructuary and exist either implicitly (through custom) or explicitly (defined by laws and regulations). For informal groundwater markets, water rights are usually implicit and defined by custom. These are known as riparian rights, and they usually connect the right to use water with the ownership of adjacent or overlying land. For surface water, the rights to use water are usually based on public allocation and prior appropriative rights [28]. Other countries are also moving toward improving the water rights structure. For instance, China has enacted laws to establish water rights. Some researchers have argued that the top priority for water user associations of developing countries should be to clarify and strengthen water rights [29,30].

Groundwater markets are known to have positive impacts on productivity and cropping patterns, especially in water-stressed regions. However, the evidence so far remains inconclusive. For instance, Singh and Singh [13] found that groundwater markets in Western Uttar Pradesh benefit the participants (buyers and sellers), with small and marginal farmers gaining more from the trade. The authors concluded that farmers should be educated about efficient water extraction devices. In contrast, Bhandari and Pandey [31] found that although water markets benefited the poor, the extent of these gains are too small and monopolistic, in which tube well owners gain more from the trading relationships of buyers and sellers. Other authors found inequities in benefit sharing and access to water. For instance, Kajisa and Takeshi [14] examined the efficiency and equity of groundwater markets in Madhya Pradesh, India, and found that output-sharing buyers pay higher water prices to sellers than do farmers under other types of contracts. So, inequities exist which depend upon the type of contracts between buyers and sellers. Similarly, Khanna [32] estimated inequities in production and income for different farmers under various water market regimes in a North Indian village. They found that water use efficiency was highest on plots irrigated by private tube wells, followed by plots served by joint tube wells, and lowest on plots owned by water buyers. In terms of crop productivity, Srivastava et al. [16] found that groundwater markets increase water access and crop water productivity of small farmers in the Central Plain Zone of Uttar Pradesh, India. Furthermore, the availability of groundwater has shifted farmers toward more water-intensive crops which are responsible for groundwater depletion.

2. Materials and Methods

2.1. Study Area and Selection of Respondents

The Punjab province in Pakistan was chosen as the study universe. We selected this province because the groundwater is extensively used, and the informal groundwater markets are most active here. Estimates show that about 76% of the cultivated area in the province is directly or indirectly dependent on groundwater to meet irrigation demand (PID, 2018). Furthermore, Punjab is the largest agricultural producer in the country [33], accounting for 63% of the total agricultural area in the country [34]. The irrigated lands in the province are in the canal command areas of the Indus Basin Irrigation System (IBIS), which is a network of rivers and canals and the main source of irrigation in the province [35]. However, there is a seasonal shortage in IBIS water supplies. Therefore, it cannot be relied upon year-round. Furthermore, the IBIS network does not cover the full province. Because of this unreliable water supply, farmers in some areas rely entirely on groundwater irrigation [36–38].

Punjab is also the province that has witnessed the most development of tube wells in the past few decades. Although there has been an unprecedented growth in tube wells in the province, not everyone can afford to install a tube well. This is because 63% of farms in the province are owned by small farmers with a farm size of fewer than 5 acres [34,39]. These farmers are usually cash-poor, and most of them cannot install their own tube wells. Due to this heterogeneity in resource endowments, informal trading of groundwater is common in the province. Farmers facing irrigation water shortages usually resort to buying groundwater from neighboring well-off farmers. The informal trading of groundwater has resulted in the emergence of groundwater markets in many areas of the province. Currently, informal markets are most active in Punjab as compared to other provinces [12,26]. Due to heavy reliance on groundwater for irrigation and higher groundwater market activity, we chose Punjab province as the sample area to study the factors influencing farmers' participation in informal groundwater. The map of Punjab and study districts is shown in Figure 1.

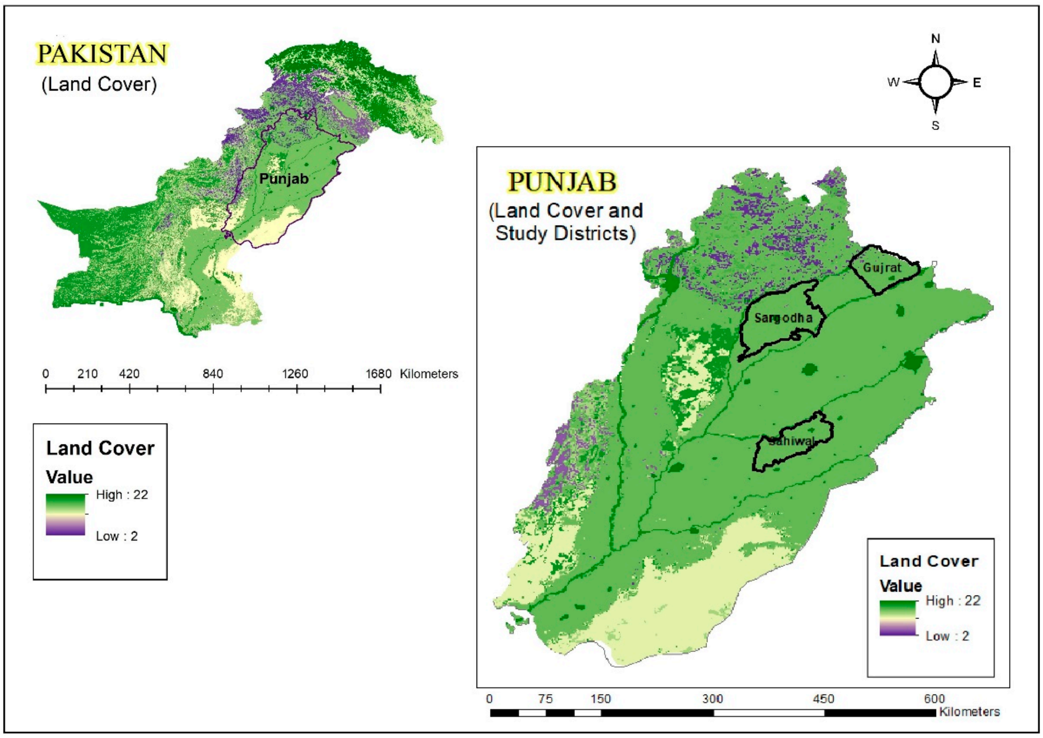

Figure 1. The location map of the study area and sample districts.

Farmers, including water buyers, sellers, and self-users, were chosen from 12 villages in three districts in the Punjab province, namely Gujrat, Sahiwal, and Sargodha, using a multi-stage sampling technique following [40–42]. In the first stage of sampling, to incorporate spatial features into the analysis for an in-depth understanding of the dynamics of groundwater markets, three districts were selected from each of the three main agro-ecological zones of Punjab. The Gujrat district belongs to the rice–wheat zone and is also a semi-arid region. The Sargodha district belongs to the mixed cropping zone, and the Sahiwal district belongs to the cotton–wheat zone. Groundwater is extensively used in all of these districts, which has resulted in the lowering of groundwater levels [5]. In addition, these districts represent a varying degree of cropping patterns, farm structures, groundwater development, precipitation rates, and groundwater market activity. These differences provide sufficient heterogeneity in the dataset to capture the spatial effects. Most farmers in Punjab are small farmers who rear dairy animals and practice subsistence farming [43,44]. There is a heavy reliance on groundwater irrigation in the study districts. In many parts of Sargodha and Sahiwal, an estimated 50–60% of the land is equipped for groundwater, while in the Gujrat district, it ranges from 70–80%. Many parts of Gujarat are semi-arid. Many parts of the district rely on groundwater for irrigation. In some areas, canal water is available during the Kharif season (April–September) [27]. Yet, canal water irrigation makes up only a very small percentage of the district's irrigation system. Therefore, groundwater irrigation is the only option for farmers. Groundwater markets have developed as a result [26]. On the other hand, canal water is available in most parts of the Sahiwal and Sargodha districts. Additionally, the groundwater in these districts is better than that in Gujarat. A moderate climate prevails in Sargodha, while Sahiwal is extremely hot in summer, averaging 45–50 degrees Celsius. In the winter, Sahiwal and Sargodha are more dependent on groundwater for irrigation, especially for the farmers at the tail ends of the canal [27].

In the second stage, two tehsils were randomly selected from each district. A tehsil is an administrative unit in Punjab and, usually, each district is divided into various tehsils. In the third stage of sample selection, two blocks (union councils) were randomly selected from each tehsil. In the fourth stage, one village was randomly selected from each block. In this way, a total of 12 villages were selected from the three districts. In the last stage, a mixture of purposive and random selection procedures was used to select the respondents. A list of all the self-users, buyers, and sellers of water was prepared from each of the sample villages, and then 10 farmers from each category were randomly selected in each village, i.e., a total number of 30 farmers (10 water buyers, 10 water sellers, and 10 self-users) were selected from each village. The final sample size from 12 villages included 360 groundwater users i.e., 120 water buyers, 120 sellers, and 120 self-users.

2.2. Survey Data Collection

A well-structured and pre-tested survey instrument was used to collect data. In a face-to-face interview, the interviewer elicited detailed information from farmers involved in water trading as well as self-users of water. The survey instrument was designed to obtain information on socioeconomic characteristics, wheat production technology, costs of production and margins of other crops, cropping patterns, and detailed information on groundwater use, tube well ownership, specifications, installation cost, the life span of tube wells, mechanism of groundwater extraction, the power source of tube wells, contractual arrangements between groundwater users, and water prices. A team of trained enumerators carried out the survey. To improve the quality of data collection, several measures including in-field training of the enumerators and pre-testing of the questionnaire were implemented. The purpose of the study was explained to respondents before collecting any data, and their verbal consent was obtained. Those farmers who refused to take part in the survey were replaced by other farmers. The survey was voluntary. We retained the records of only the participants who expressed their willingness to participate in the study.

2.3. Analytical Framework

The following analytical techniques were used to estimate the impacts of groundwater markets on different outcomes.

2.3.1. Measurement of Equity

Different measures were used to assess the equity impacts of groundwater markets. These are described below.

2.3.2. Horizontal Equity

In essence, horizontal equity refers to distributing groundwater equally across different types of markets. Since we measured the actual volumetric access of groundwater for wheat, therefore, it was used as the proxy variable for water access. The significance of the impact of different forms of water markets was determined using an ANOVA (*F*-test) on the volume of water applied and the yield of the wheat crop. The following hypothesis was tested:

H0 (null hypothesis): $\mu_1 = \mu_2 = \mu_3 = \ldots \mu_k$, i.e., the mean of the variable under consideration (quantity of groundwater or wheat yield) will be equal under k forms of water market regimes (buyers, sellers, self-users). In this case, the F statistic is:

$$F_{k-1,\, n-k} = \frac{MS_M}{MS_E}$$

where MS_M is the mean square of the variable under a water market, MS_E is the error mean square, and n is the total sample size. If the ANOVA test finds that the mean of the variable under consideration for different water market regimes is statistically significant, Scheffe's multiple comparison method was used to determine the source of such differences between any two water market types. Two different types of water markets, buyers (B) and sellers (S), can be compared using this method by testing the hypothesis H0: $\mu S - \mu B = 0$.

The method entails constructing a Scheffe-type confidence interval on the comparison of interest as follows:

$$\sum_{i=1}^{k}, \alpha_i \overline{X_i} - L \leq \sum_{i=1}^{k} \alpha_i \mu_i \leq \sum_{i=1}^{k} \alpha_i X_i + L \text{ and} \tag{2}$$

$$L^2 = (k-1)\, f_{\alpha,k-1,N-k}\, MS_E \left(\sum_{i=1}^{k} \frac{a_i^2}{n_i} \right) \tag{3}$$

where $f_{\alpha,k-1,N-k}$, MS_E and X_i represent the critical points used in rejecting or accepting hypotheses, error mean square based on an ANOVA, and factor means, respectively, under the *i-th* form of the water market. The comparison between the means of the factor under consideration under any two forms of the water market is significant if the numerical interval constructed at the appropriate significance level does not contain zero.

The coefficient of variation was estimated as follows:

$$\text{C.V. } (\%) = \frac{\sigma}{\overline{X}} \times 100 = (\text{Standard deviation}/\text{Average}) \times 100 \tag{4}$$

2.3.3. Vertical Equity

Vertical equity is defined by keeping in view the main view of society, which refers to the extent to which the effects of groundwater markets extend to a particular social or economic class at the expense of others (e.g., between small and large farmers).

Various methods were used to capture the vertical equity. In order to determine the relative access to groundwater by farms of different sizes under any type of water market, it was hypothesized that if large farmers have access to groundwater to a higher degree, then their productivity would be higher. The Cobb–Douglas production function was used to test the land productivity–farm size relationship. Wheat productivity was used as a proxy indicator of the fairness of groundwater access.

In addition, various measures of income inequality such as the Gini coefficient, the mean log deviation (MLD), and coefficient of variation (C.V.) were calculated. Following Edwards [45] and Naseer et al. [46], the Gini coefficient ratio was calculated as follows:

$$\text{Gini coefficient} = \frac{\sum_{i=1}^{n=1} X_{i+j} Y_i}{\sum_{i=1}^{n=1} X_i Y_{i+j}} \tag{5}$$

where

X_i = cumulative percentage frequency w.r.t number of farmers corresponding to a particular landholding size in acres (X_i = 1, 2, 3, . . . , n)
Y_i = cumulative frequency percentage w.r.t wheat gross margins (PKR/acre) corresponding to a particular farm size (acres) (Y_i = 1, 2, 3, . . . , n)
X_{i+1} and Y_{i+1} = preceding observation of X_i and Y_i, respectively

Furthermore, a Lorenz curve was constructed for different farm size categories. The extent to which the Lorenz curve departs from the equality line (diagonal line) indicates the extent of inequality in income distribution [47].

It is also possible to measure income equality using the mean log deviation. If incomes are equal, then MLD is zero, but it increases as income becomes more unequal, especially at the top end. According to Haughton and Khandker [48], the MLD of the household income is defined as:

$$\text{MLD} = \frac{1}{N} \sum_{i=1}^{N} ln \frac{\overline{x}}{x_i} \tag{6}$$

where N is the number of farms, x_i is the income of a farming household i under a water market, and $\overline{x}$ is the mean of x_i. The equivalent definitions of MLD are:

$$\text{MLD} = \frac{1}{N} \sum_{i=1}^{N} (ln\, \overline{x} - ln\, x_i) = ln\, \overline{x} - \overline{ln\, x} \tag{7}$$

where $\overline{ln\ x}$ is the mean of $ln(x)$. The MLD definition indicates that it is non-negative, since $ln\ \overline{x} \geq \overline{ln\ x}$ by Jensen's inequality [49].

2.3.4. Impact of Different Sources of Irrigations on Plot-level Wheat Yields

We estimated a production function based on survey data to find out how groundwater market participation impacts wheat yields. The production function was estimated for wheat only due to the limited degrees of freedom for other crops in the sample. Additionally, wheat was the only staple crop that was grown by all farmers in the sample. The model was as follows:

YWHEAT = fn (LABOR, SEED, FERTILIZER, CHEMICALS, HYV, FERTILITY, BUYGWATER, CANALWTR) (8)

where

YWHEAT = wheat yield in kg/acre
LABOR = hours of family and hired labor per acre
SEED = seed rate, kg/acre
FERTILIZER = quantity of fertilizer (urea, DAP, MOP, SOP, etc.) in kg/acre
CHEMICALS = number of chemical applications (pesticides, herbicides, fungicides) per acre
HYV = 1 if the farmer uses a high-yielding wheat variety
FERTILITY = 1 if farmers reported the soil on wheat plots to be fertile
BUYGWATER = 1 if the farmer purchases groundwater for irrigation
CANALWTR = 1 if the farmer also has access to canal water for irrigation

This type of analysis separates the impact of different sources of irrigation. Furthermore, we can distinguish the groundwater applied from purchased sources and own tube wells. The reason for including canal water as a variable in the model is that it is widely assumed that canal water is of high quality and yields higher returns. So, we hypothesize that it has a positive impact on yield. Although we were able to reduce selection bias in the choice of these variables by using a multistage random sampling procedure, it cannot be completely mitigated.

2.3.5. Impact of Participation in Groundwater Markets on Farmers' Income (Propensity Score Matching)

In assessing the farmers' decision to participate in water markets and its relevant impact on farm incomes, a random utility framework was employed following Kato et al. [50]. The main motivation of the farmer to participate in water markets is improving well-being (sellers and buyers) and reducing crop losses associated with the unavailability of adequate irrigation water (buyers). A water seller might be interested in participating because s/he wants to earn some extra income from selling water, while a buyer wants to increase productivity by applying irrigation water to the crops. For both types of farmers, the net benefit difference can be indicated as:

$$U_i^* = \beta X_{ik} + \varepsilon_i \tag{9}$$

where U_i^* is the unobservable latent variable, X_{ik} is a vector of explanatory variables, the β is a logistic regression coefficient, and ε_i is the error term. In this case, the corresponding observable part of U_i^* is:

$$U_i = \begin{cases} 1, & if \quad U_i^* > 0 \\ 0, & if \quad U_i^* \leq 0 \end{cases} \text{; and} \tag{10}$$

In Equation (9), the ith farmer will participate ($U_i = 1$) in the water markets if the net benefit of participation is positive, i.e., $U_i^* > 0$. In contrast, a farmer does not participate if s/he perceives the net benefit to be non-positive, i.e., $U_i^* \leq 0$.

The farmer welfare and net income are associated with many variables and their relative efficiency of utilization. Differentiating the welfare effects for participants and non-participants of water markets is not an easy task. However, it might be easier to achieve this distinction in experimental data that is composed of randomized information against the counterfactual position. In the case of no counterfactual information, the outcomes of participants and non-participants may be biased or misleading [51]. So, there may be a problem of self-selection bias in assessing the impacts of water market participation on farmers' well-being or net income. Such a comparison will be biased because of differences in the characteristics of the two groups. The importance of this self-selection bias can be indicated by looking at the assumptions of the ordinary least square (OLS) reduced form equation, which links the relationship of farmers' income and with explanatory variables as follows:

$$Y_{ij} = \gamma X_{ik} + \delta \, U_i + \mu_i \tag{11}$$

where Y_{ij} is the vector of outcome variables (income and productivity), μ_i is the error term, X_{ik} is a vector of explanatory variables, and γ and δ are the regression coefficients. These regression coefficients are also called the slope and measure the steepness of the regression line. Now, the main concern is whether the participation decision U_i is independent when the unobserved variables influence farmers' managerial skills, etc. It is right to expect that the error terms in Equations (9) and (11) are correlated, which may produce biased estimates [52,53]. Several approaches have been used to overcome this bias. For instance, Heckman's two-step method has been used in several studies. Furthermore, the instrumental variable approach is also suggested, but in reality, it is difficult to identify a suitable instrument [54]. One useful approach to solve the problem of self-selection bias is the propensity score matching (PSM) technique. Using a list of control variables, the PSM estimator constructs a comparison group that can match participants and non-participants, i.e., X_{ik} is controlled for all unobserved factors. Thus, the propensity score matching can be presented as:

$$P(X_{ik}) = Pr\,[U_i = 1|X_{ik}] \tag{12}$$

where P indicates propensity score, U_i indicates the participation in water markets, Pr indicates probability, and X_{ik} indicates the characteristics of the respondent's pre-participation. The participants and non-participants are assumed to have a similar conditional distribution of X_{ik} [53].

Our main goal is to assess the average treatment effect (participation) on the treated (participants). It can be expressed as follows:

$$ATT = E(Y_1 - Y_0 \;|U_i = 1) = E[(Y_1 - Y_0|U_i = 1\,),\; P(X)] = E(Y_1|U_i = 1) - E(Y_0|U_i = 0) \tag{13}$$

where $U_i = 1$ indicates that the farmer experiences the treatment, i.e., participates in the water markets, and $U_i = 0$, otherwise. Likewise, $Y_1 = 1$ is the outcome variable when the farmer experiences the treatment, and $Y_1 = 0$, otherwise. Since we could not observe the two outcome variables simultaneously, therefore we used the PSM method. The one-to-one matching, nearest neighborhood methods (NNM), and kernel methods were used to study participants and non-participants. The unmatched groups were excluded, while matched groups of participants and non-participants were included in the analysis [55]. The conditional independence is the primary assumption of the underlying matching estimator, which stipulates that the participants and non-participants of water markets have a similar mean outcome under a particular set of observable variables (Heckman and Navarro-Lozano 2004). The outcome variable in our case is the total farm income of the respondents.

2.3.6. Measurement of Volume of Groundwater Extracted

The amount of groundwater used for irrigation was estimated indirectly using the information on tube well 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 tube well. Following Srivastava, Kumar, and Singh [16], Eyhorn, et al. [56], Watto and Mugera [57], and Razzaq, Qing, Naseer, Abid, Anwar, and Javed [26], a pre-tested formula was used to estimate the quantity of groundwater applied to wheat crop:

$$Q = \frac{t \times 1295741.1 \times BHP}{d + (255.5998) \times BHP^2)/d^2 \times D^4} \quad (14)$$

where Q stands for the amount of groundwater extracted (liters), t stands for the duration of irrigation (hours), d is the depth of the borehole (meters), BHP is the engine power of the pump (HP), and D stands for the diameter of the pump suction pipe (inches). We converted the quantity of water to cubic meters to include in the calculations.

3. Results and Discussion

3.1. Water Markets and Cropping Pattern

The results related to cropping patterns across different water market regimes are presented in Table 1. Overall, more than 3000 acres were cultivated by sample farmers, out of which water buyers and sellers occupied about 33% of the net sown area, The net sown area was defined as the total area sown with crops and orchards. Area sown more than once in the same year was counted only once. However, the gross cropped area (i.e., the total area sown once and/or more than once in a particular year) of these farmers was 41%, indicating a higher cropping intensity among water market participants. The cropping intensity was defined as the ratio of gross cropped area to net sown area. The results show that the highest cropping intensity was among water buyers (169%), followed by water sellers (165%). The self-users had the lowest cropping intensity, indicating that much of their land was idle. These results indicate that participation in water markets increases the utilization of agricultural land. These results are consistent with those of Singh and Singh [13], who found a similar pattern of higher cropping intensities among water market participants in the Western Uttar Pradesh region of India.

Wheat occupied the highest proportion of total cropped area across all forms of water markets. However, on buyers' farms, the share of wheat was lower than that of water sellers and self-users. For these small farmers, fodder (winter and summer) occupied about 35% of the cropped area. This is because most small farmers also rear dairy animals to fulfill their cash needs as the income from selling milk is realized relatively sooner than the crop incomes. Compared with buyers, large farmers (sellers and self-users) dedicated more area to major crops such as rice, cotton, maize, potato, and citrus. However, the results indicate that water markets have provided ample opportunity to small and marginal farmers to grow a diverse number of crops, which would not have been possible otherwise.

Table 1. Cropping pattern, cropping intensity, and total cropped area across the water markets.

Particulars	Buyers	Sellers	Self-Users	Overall
Number of farmers	120	120	120	360
Average farm size (acres)	2.36	6.58	17.86	8.93
Net sown area (acres)	283.13	789.75	2143.00	3215.88
Gross cropped area (acres)	480.38	1305.00	2504.05	4289.43
Cropping intensity (%)	169.67	165.24	116.85	133.38
Crop share in the gross cropped area (%)				
Wheat	35.16	43.72	45.74	43.94
Rice	7.60	8.58	9.71	9.13
Cotton	2.91	4.10	8.47	6.52
Citrus	2.08	6.17	10.60	8.30
Maize	3.12	6.13	9.46	7.74
Potato	4.58	6.74	5.87	5.99
Fodder: *Kharif* †	28.42	15.06	5.93	11.23
Rabi †	6.51	4.20	1.19	2.70
Sugarcane	2.50	1.92	1.59	1.79
Others	7.13	3.39	1.44	2.67

† *Kharif* and *Rabi* indicate summer (spring, monsoon) and winter (autumn) cropping season, respectively.

3.2. Access to Groundwater Irrigation

Results of groundwater irrigation access for different farmer groups are presented in Table 2. Based on the size of landholdings, we further divided farmers' groups into marginal, small, and large farmers. The results indicate that all marginal farmers purchased water. The water purchasers under this category irrigated 163 acres of farmland. The groundwater market provided them with the opportunity to irrigate the land by purchasing water. However, the share of water buyers in the smallholder category was about 30%, who irrigated roughly 23% of the total land in this category. Under the smallholder category, 45% and 31% of the total farm area was irrigated by water sellers and self-users, respectively. Farmers in the third farm size group had relatively large farms. A small fraction of water buyers (6.63%) belonged to this group. Across the sample, self-users irrigated the most farmland.

Table 2. Groundwater access and farmers' area under different forms of water markets.

Farm Category	Water Buyers		Water Sellers		Self-Users		Overall	
	HH † (%)	Farm Area	HH (%)	Farm Area	HH (%)	Farm Area	HH (%)	Farm Area
Marginal (0–2.5 acres)	100	163.88 (100)	0.00	0.00 (0.00)	0.00	0.00 (0.00)	100	163.88 (100)
Small (2–2.5 acres)	30.25	112.25 (23.54)	40.34	216.5 (45.41)	29.41	148 (31.04)	100	476.75 (100)
Large (>5 acres)	0.63	7.00 (0.27)	45.57	573.25 (22.26)	53.8	1995 (77.47)	100	2575.25 (100)

Notes: Figures in parenthesis for farm area indicate the percentage of the total area under the respective farm size category. † HH = households.

Approximately 8% (283 acres) of the irrigated area of surveyed farmers was owned by water purchasers. In the absence of groundwater markets, water buyers will find it difficult to irrigate their land with groundwater. These markets transfer water from large farmers to smaller farmers, allowing resource-poor farmers convenient access to water. According to our findings, the groundwater markets positively influenced the distribution of groundwater in the studied area. These findings are in line with the studies of [12,16,58,59]. Being a water buyer has its downsides, however, in that water supply timing and reliability can be less predictable.

3.3. Equity Impacts of Water Markets

3.3.1. Horizontal Equity

The ANOVA test was used to perform a horizontal equity analysis of groundwater markets, which revealed that the number of irrigations applied varied in wheat, resulting in differences in wheat yield among different types of water markets (Table 3). The total number of irrigations applied by buyers (3.64) was slightly lower than the number of irrigations applied by water sellers (4.09) and self-users (4.27). The Scheffe test indicated that these differences were significant. Furthermore, buyers' yield (1465 kg/acre) was significantly lower than that of sellers (1680 kg/acre) and self-users (1548 kg/acre).

These findings show that tube well owners (both sellers and self-users) had better physical access to water, resulting in higher wheat yields on their farms. The increased yield was the product of a combination of input usage and water markets. At the same time, the type of water market affected the amount of input used. As a result, improvements in yield were related to better accessibility in water markets. These findings show that there are physical inequities in access to water, with tube well owners irrigating their crops more often because they have more control over irrigation timing. These findings are consistent with the study of [13], in which the authors found that self-users and self-users + sellers had greater control over water supply.

Table 3. Level of irrigation and wheat yield achieved under different water market regimes.

Particulars	Irrigation (Numbers)	CV (%)	Yield (40 kg/acre)	CV (%)
(a) Water buyers	3.64	14.59	1465	14.90
(b) Water sellers	4.09 [a]	8.97	1680 [a]	9.65
(c) Self-users	4.27 [b]	13.82	1551 [b]	16.04
(b and c) Tube well owners	4.18 [c]	11.91	1615 [c]	13.57
Overall	4.00	14.20	1565	14.69

'a', 'b', and 'c' indicate that difference from water buyers is significant at a 1% level of significance.

3.3.2. Vertical Equity

Within a particular type of water market, the vertical equity analysis focuses on the economic as well as physical equity in groundwater access. The economic equity in the water markets is analyzed by comparing the net returns among different sizes of farms. We found that under almost all types of water markets, the estimated regression coefficient of the log-linear production function of land revealed a negative relationship between farm size and wheat yield (farm size = independent variable, wheat yield = dependent variable), suggesting no physical inequity in access to groundwater (Table 4). We used the variable of farm size because large farmers usually have greater access to groundwater as they own the tube wells. Furthermore, the R^2 values in these cases were found to be exceptionally low, suggesting that the difference in yield was due to factors other than groundwater accessibility.

Table 4. The estimated relationship between farm size and wheat yields under different water market regimes.

Water Markets	Constant	Elasticity (Regression Coefficient)	R^2
Buyers	3.600	−0.014	0.001
Sellers	3.859	−0.070 ***	0.054
Self−users	3.694	−0.021	0.008
All farms	3.631	0.013	0.004

*** indicates significance level at 1%.

Furthermore, the degree of inequity in net returns per acre was used as a proxy variable to investigate the extent of economic inequity in groundwater markets. The Lorenz curve (Figure 2) and various other indicators of income inequality were calculated (Table 5). Inequality in agricultural return distribution was measured by the distance of the Lorenz curve from the diagonal line: the further the curve deviated from the diagonal line, the more inequitable the farm income distribution, and vice versa.

Table 5. Measures of income equality across water markets.

Inequity Measures	Buyers (1)	Sellers (2)	Self-Users (3)	Tube Well Owners (2 and 3)	Overall (4)
Gini coefficient	0.187	0.109	0.171	0.141	0.157
Mean log deviation (MLD)	0.085	0.025	0.147	0.086	0.086
Coefficient of variation (CV)	0.335	0.203	0.313	0.262	0.287

According to indicators of income inequality (Table 5), as well as the Lorenz curve (Figure 2), net returns from groundwater irrigation were more equally distributed among tube well owners than among water buyers. However, the gap is not big. The gap between water buyers and self-users, according to the various income inequality measures, is very small. These findings show that, while being small and marginal farmers, water buyers can achieve an equitable distribution of net returns comparable to large farmers (self-users). Furthermore, a comparison of water sellers and self-users reveals that water sellers' net returns were more evenly distributed. These findings suggest that, regardless of farm size, participation in water markets improves economic equity in the study area. These results are consistent with the findings of [13,60].

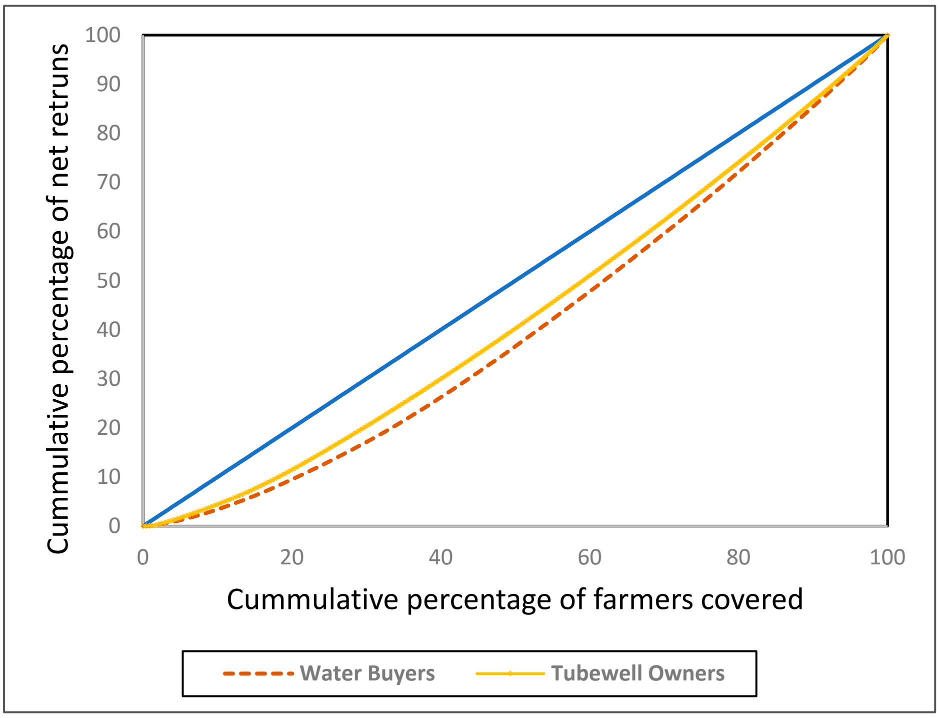

Figure 2. Distribution of net returns to cultivation across water markets.

3.3.3. Impact of Groundwater Markets on Wheat Yields and Water Productivity

A production function was estimated using farm-level data on sample farmers to analyze the effect of various irrigation sources on yields. Because of the limited degrees of freedom for the other crops grown by the sample farmers, this equation was only estimated for wheat, a staple crop cultivated by roughly all farmers in all districts.

This estimation, unlike traditional production functions, separates irrigation applications by source. It also differentiates between groundwater applications bought from other farmers. Canal applications should contribute more than groundwater because canal water is generally of higher quality, whereas purchased groundwater applications should have about the same effects unless there are variations in the degree of control and reliability of irrigation applications for various sources.

The results of this estimation using a linear yield function are shown in Table 6. We also tried Cobb–Douglas and log-linear functional forms as alternatives, but they did not fit the data as well as linear regression. The quadratic and interaction terms were tested but found to be non-significant, so they were left out of the model.

Wheat yields are strongly influenced by soil fertility and the adoption of high-yielding wheat varieties. Higher yields are also linked to seeding rate and fertilizer use. In addition, both forms of irrigation inputs were found to have a significant positive effect on wheat yields, after adjusting for fertilizer input and soil fertility. Purchased groundwater has a significant and positive coefficient, implying that purchasing water was associated with higher wheat yields. These findings indicate that participating in groundwater markets improved crop yields for water buyers. These findings are consistent with the study of [12] in the Pakistani provinces of Punjab and Khyber Pakhtunkhwa.

Table 6. Effect of sources of irrigation on plot-level yields in the study area.

Explanatory Variable	Coefficient	Standard Error	t-Static	Variable Mean
Labor	0.002	0.005	0.391	44.48
Seed	0.137 ***	0.046	2.979	51.88
Fertilizer	0.026 ***	0.008	3.469	119.63
Chemicals	0.359	0.43	0.834	1.20
HYV	1.343 **	0.523	2.568	0.53
Fertility	1.311 ***	0.499	2.628	0.62
BUYGWATER	2.235 ***	0.673	3.321	0.33
CANALWTR	7.388 ***	0.658	11.232	0.44
Constant	22.771 ***	2.473	9.207	
Adjusted R^2	0.492			
Number of observations	360			

** and *** indicate significance levels at 5%, and 1%, respectively

Water productivity, which measures output per cubic meter of water used, can also be used to measure irrigation's impact on productivity. Although it is not the most effective metric, this criterion is often used to compare the water use efficiency of various crops. Table 7 shows the amount of water used in wheat crop and water productivity for various farmer groups. The amount of water used in wheat estimated in our study is comparable to that in another study in Pakistan that estimated average water use of 3459 m^3/acre for tube well owners and shareholders, and 2470 m^3/acre for water buyers [34]. The average water use for irrigated wheat in China is 3211 m^3/acre, however, the water productivity in China is 0.8 kg/m^3, compared to 0.44 kg/m^3 in our study [59]. These findings also imply that farmers in China use 1.24 m^3 of water to produce one kg of wheat, whereas farmers in Punjab use 2.25 m^3 of water to produce the same amount of wheat. This disparity is due to lower yields in Punjab as well as a lack of use of water-saving technologies. Farmers in Pakistan, particularly in Punjab province, mostly use the flood irrigation method to irrigate the wheat crop. All the farmers in our sample also reported using the flood irrigation method. However, it should be noted that the results of water productivity could vary if the farmers use different irrigation methods for a particular crop. Across farmer groups, the results of water productivity in wheat crops show that buyers used the least amount of water and generated the highest water productivity. Self-users had the lowest water productivity of any of the three classes. This is because they applied more water for irrigation than buyers and had a lower yield. While sellers used the most water per acre of wheat, their yield was higher than self-users', so their water productivity was equal to that of water sellers. Water productivity in wheat crops was 0.55, 0.40, and 0.40, respectively, for buyers, sellers, and self-users. Self-users who did not engage in water markets and used water for their own purposes had lower water productivity than the water buyers, indicating that groundwater markets have a positive effect on water use efficiency. Ref. [60] found similar results in India. In addition, Srivastava et al. [16] also found that, compared to other categories of water users such as self-users, and self-users plus sellers, water productivity for the water buyers category was higher in wheat, sugarcane, and potato crops.

Table 7. Water productivity across different water markets.

Water Markets	Water Use (m^3/ac)	Crop Yield (kg/ac)	Water Productivity (kg/m^3)
Buyers	2656.55	1465.00	0.55
Sellers	4237.06	1679.98	0.40
Self-user	3816.67	1551.17	0.40
Overall	3533.79	1565.38	0.44

The incremental output ratio, which is a measure of net returns per cubic meter of water, shows that buyers had significantly higher net returns per cubic meter of water as compared to water sellers and self-users. On average, a cubic meter of groundwater used for irrigation brought net returns of PKR 7.33 (Figure 3). The net returns per cubic meter of water were higher for water buyers and sellers (participants) than self-users (non-participants), indicating that water market participants combined inputs more efficiently to generate higher net returns. Similarly, Srivastava et al. [16] found that water buyers in Lucknow and Sitapur districts of India had higher water-output ratios for wheat, sugarcane, and potato crops. The higher incremental output ratio for water buyers indicates economic behavior by these farmers who also had to pay higher costs for water use. Therefore, they must have either used less water or produced more output to generate profits. In other words, water markets promote profit-maximizing behavior by assigning a higher cost to water for these farmers.

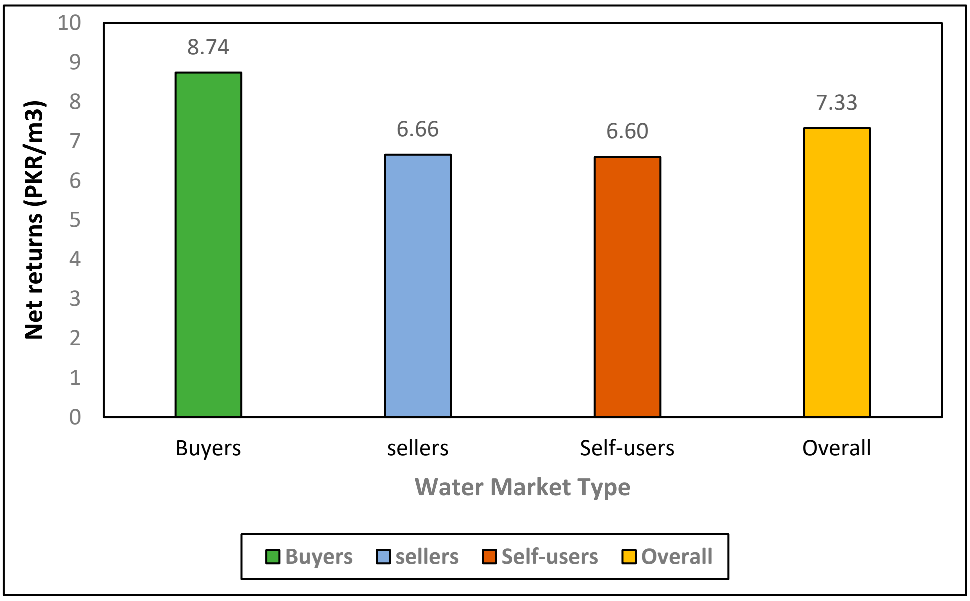

Figure 3. Incremental output ratio across water markets.

3.3.4. Impact of Participation in Water Markets on Farmers' Income

To estimate the effect of participation in water markets on income and productivity, propensity score matching was used. After measuring the propensity scores, the control group (non-participants, i.e., self-users) was matched to the treated group (participants in water markets, i.e., buyers and sellers) using Kernel matching, one-to-one matching, and nearest-neighbor matching (NNM) methods. The NNM discards unmatched non-participants during the matching process, resulting in a reduction in sample size. Therefore, we compare the outcomes of different matching methods. The average effects on wheat productivity (kg/acre) and per acre net crop income before (ATE, i.e., average treatment effect) and after (ATT, i.e., average treatment effect on the treated) matching were determined next (Table 8).

The post-matching results show that water market participation had a positive and significant effect on wheat productivity and crop income. According to the ATT values, participants' wheat yield was higher by approximately 150 kg/acre than non-participants'. Participation in water markets also raised participants' returns by around PKR 4503 per acre. In contrast to the ATT figures, the ATE values display lower yield gains (approximately 115 kg/acre) and crop income improvements (PKR 3500 per acre). The disparity between the ATT and ATE values is primarily due to selection bias induced by other observable factors, which was eliminated using the propensity score matching technique.

Table 8. Impact of participation in water markets on productivity and net crop income.

	PSM Method	ATE	ATT
Wheat yield (kg/acre)	Kernel	120.56	153.05 (38.53) ***
	One-to-one	116.60	150.24 (57.07) ***
	Nearest neighbor	105.13	150.24 (47.71) ***
Crop income (PKR/acre)	Kernel	3611.84	4869.91 (1451.07) ***
	One-to-one	3478.96	4503.39 (1822.23) ***
	Nearest neighbor	3076.65	4503.39 (1554.70) ***
Indicators of covariate balancing before and after matching			
Indicators		Before matching	After matching
Pseudo R^2		0.179	0.055
p-value of likelihood ratio		0.000	0.62

*** indicate significance at 1% level of significance.

Higher yields and returns for participants also indicate that participation in water markets had a positive effect on farmers' overall well-being. These results are consistent with the study of Meinzen-Dick [12], who found that groundwater markets increase the level of agricultural productivity and farmer income. Moreover, the increased yields due to water market participation (150 kg/acre) could result in 490,500 kcal of additional supply per acre, which might be able to reduce the gap between supply and demand for food calories and boost food security.

4. Conclusions

This study assessed the impacts of water markets on the equity and productivity of farmers in Punjab, Pakistan. The equity analysis was conducted using various techniques such as ANOVA and various inequity measures such as Gini coefficient, mean log deviation (MLD), coefficient of variation, and Lorenz curve. The effects of water markets on productivity and income were assessed using a multivariate analysis of the relationship between plot-level wheat yields and various explanatory variables including sources of irrigation. Furthermore, water productivity and the incremental output ratio of water were calculated for different forms of water markets. Finally, the propensity score matching technique was employed to assess the impact of water markets on farmers' incomes, in which outcomes were compared for participants and non-participants of water markets.

We find that informal groundwater markets are still relevant in the province and continue to benefit farmers. In particular, water markets lead to increased agricultural land utilization since buyers and sellers had far greater cropping intensity than self-users. In addition, these groundwater markets facilitate the transfer of water from large farmers to small farmers, thus providing convenient access to water for resource-poor farmers. In the horizontal equity analysis, the tube well owners (sellers and self-users) were found to have better access to irrigation, resulting in higher wheat yields on their farms. Vertical equity analysis, however, showed that variations in yield were caused by factors other than accessibility to groundwater. Furthermore, the measures of income inequality showed that water buyers, despite being the small and marginal farmers, could realize net returns which were comparable to those of large farmers. This finding implies that participation in water markets improved income distribution in the study area irrespective of farm size. The results also showed that participation in groundwater markets helped water buyers to realize better crop yields that were comparable to those of large farmers. This was further confirmed by higher water productivity and incremental output ratio of water for water buyers.

The results of the propensity matching score showed that participants of water markets produced about 150 kg/acre more wheat than non-participants and generated about PKR 4503 per acre more returns for participants. A higher level of productivity and crop income for water market participants suggests a positive effect on farmers' overall welfare.

Overall, the study confirms the relevance of groundwater markets in Punjab, Pakistan, and supports the claim that water markets provide substantial benefits to farmers by enhancing their income and equity of access to water. However, efforts are needed to curtail the overextraction of groundwater because the water markets in their current form have no inherent mechanism to control the overuse of groundwater. Although water sellers seem to earn profits from the selling of water, there are still many tube well owners who do not participate in water markets and continue to operate with lower efficiency. Keeping in mind the economic benefits of water markets as well as their limitations in controlling the overexploitation of water, the government needs to consider the benefits and limitations of groundwater markets in its Punjab Water Act.

Furthermore, water users could be encouraged to adopt participatory irrigation management approaches to jointly control the overexploitation of groundwater. These organizations could formulate rules and regulations aimed at reducing water use to improve the welfare of the whole community by using groundwater irrigation more efficiently. To ensure the sustainability of groundwater use, farmers' incomes, and food security of the population, there is an urgent need to devise policy options to improve the water use efficiency in the province. Pakistan has taken some steps to improve groundwater management. The Punjab Water Act of 2019 is perhaps the most important of these measures, in which the government attempted to define water rights, devise a pricing mechanism for groundwater, and encourage the use of water conservation techniques. In addition, the new law has implications for groundwater markets because it focuses on water rights and water pricing. Although the newly introduced Punjab Water Act 2019 raises a lot of questions about groundwater management, it is not clear how the state will establish a system of tube well licensing and abstraction under the new legislation. The findings of our study may provide policymakers with valuable insights as they implement the new law.

Limitations and Future Research

There are a few limitations to our study. First, despite carefully selecting Punjab province based on its higher water market activity and the highest agricultural production share in the country, other provincial water markets exist in Pakistan. Nevertheless, we were unable to collect data from provinces other than Punjab because of financial and time constraints. Even so, we believe that including data from other regions will give a more complete picture of Pakistan's water markets. Second, we focused on the groundwater market because groundwater is the most widely traded resource among farmers. However, because of the complex allocation system for surface water in Punjab, many farmers are now purchasing canal water shares, resulting in the birth of surface water markets. It would be worthwhile to investigate whether any interactions between these two different water markets affect Punjab's overall allocation of irrigation water. Finally, this study was limited to the assessment of groundwater water markets that are relevant to agriculture. In recent years, however, groundwater markets for non-agricultural purposes have emerged in several regions because of groundwater shortages. The limited supply of groundwater could leave agricultural and non-agricultural buyers in competition. A future study may also examine non-agricultural groundwater markets to determine whether they impact agricultural water markets, especially prices and contracts.

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