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TECHNICAL AND GROUNDWATER USE EFFICIENCY IN WHEAT-MAIZE CROPPING PATTERN: AN EVIDENCE FROM BARI DOAB, PUNJAB PAKISTAN

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ABSTRACT

In Pakistan, the agricultural production chain depends on multiple factors, out of which irrigation is considered as the primary input. With the passage of time, this country's resource base is diminishing rapidly and adversely affecting the rural economy. To cope with the demand of the expanding population, efficient utilization of this resource is crucial. This study aims to examine the relationship between technical efficiency and groundwater use efficiency in the wheat-maize cropping pattern from Central Punjab, Pakistan. For this purpose, the Depalpur distributary was selected from Bari doab. Primary data from 214 farmers of Okara district (Central Punjab) were collected through a multi-stage sampling technique. Various factors affecting technical and groundwater use efficiency were investigated using the Tobit model (Bootstrap truncated). Results indicated that wheat and maize farms were achieving higher level of technical efficiency (0.94 & 0.92, respectively) than groundwater use efficiency levels (0.63 & 0.64, respectively). The results suggested that improving groundwater efficiency could decrease excessive extraction of groundwater consequently achieving higher returns from wheat and maize remaining on same level of groundwater. Tobit analysis indicated that education status of farmers, farmer experience, agricultural extension services and ownership of tube well would result in achieving higher level of technical and groundwater use efficiencies.

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INTRODUCTION

Groundwater is a blessed substitute of surface water, particularly in the time of drought at initial stages (Mussá et al., 2015, Ajaz et al., 2019, Wheeler et al., 2021, Scanlon et al., 2023). The expansion of agriculture production and poverty stricken rural areas in the Indian sub-continent heavily depend on groundwater where surface water is limited (Changming et al., 2001; Dangar et al., 2021). Farmers in rural areas meet nearly 40 percent of agricultural produce requirements through the pumping of groundwater (Dalin et al., 2017). This dependence on groundwater has been steadily increasing due to intensive agricultural production,

uncertain rainfall patterns, limited availability of surface water, and the rising food requirements of a growing population (Pathak and Dodamani, 2019; Wada et al., 2012). Fresh water is approximately 2.5 percent of total global water resources, out of which groundwater accounts for 30 percent (USGS, 2021). Over 85 percent of extracted groundwater is allocated for irrigation purpose in the continent (Mukherjee et al., 2015), whereas the global average is around 40 percent (Siebert et al., 2015; Chindarkar and Grafton, 2019). India, Pakistan, and Bangladesh are among the top countries in groundwater usage, with estimated annual withdrawals of 230 billion m³,

60 bm^3 and 30 bm^3 respectively (Subhadra, 2015; Qureshi, 2015; Suhag, 2016). These countries are using approximately 42 percent of global groundwater for 387 million hectare of crop land (Mukherjee et al., 2015).

As the world's third largest consumer of groundwater, Pakistan withdraws around 9 percent of the global freshwater resources (Giordano, 2009) which supports approximately 4.6 percent of the irrigated crop land area (Bhutta and Smedema, 2007). Use of groundwater was enhanced after a government funded project "Salinity Control and Reclamation Project" (SCARP), launched in 1960 to mitigate salinity and waterlogging issues. This model added fuel to the fire, encouraging farmer to begin installing their own tube wells. In Punjab province, farm gate water supply increased from 8 percent to 75 percent between 1960 and 2018 (Qureshi, 2018; Asghar et al., 2018). In contrast, the contribution in Sindh, Khyber Pakhtunkhwa and Baluchistan was 4.4 percent, 1.8 percent, and 3.8 percent respectively (Qureshi, 2020). After Green Revolution of 1960's, the demand of groundwater has increased (Ahmad et al., 2009) to compensate for shortage in surface water. Furthermore, the groundwater wells installation was increased by 59 percent when surface water availability was cut down to 26 percent by a severe drought during 1998-2002 (Bhutta, 2002). At present, 1.18 million tube wells (electric and diesel) are working to irrigate 17.04 million hectares in the Punjab province (STATISTICS, 2024)

Although the access to groundwater is unrestricted, due to which farmer's cropping patterns are diversified, cropping intensity has increased, crop yield has improved which ultimately resulted in poverty reduction and boosting of economic development as compared to past (Qureshi, 2018). At this time approximately 2.5 million rural peoples of Pakistan are irrigating their fields using groundwater coupled with surface water (Qureshi, 2011). Various researchers (Shah, 2007; Shah et al., 2003) exhibited that the crop production of groundwater using farmers increased by 50-100 percent than those who were exclusively rely on canal water. Wheat, cotton, sugarcane, maize and rice are the most important produces of Pakistan. These major crops contributes 17.82 percent to value addition and serve as vital sources of food, foreign exchange and raw ingredients for domestic industries (GOP, 2025). Despite the notable contribution of major crops, Davis et al., 2018 concluded that rice and wheat cropping pattern is the water intensive cultivation and suggested shifting with maize, millet or pulses to reduce water demand by up to 33 percent. Alexandratos and Bruinsma, 2012 forecasted 66 percent of

maize production is required by 2050 to meet the global demand. Compared with rice, maize tolerates water stress at particular growth stages and yields higher returns (Zou et al., 2021). Attia et al., 2021 suggested that groundwater use efficiency is higher during the vegetative stage of maize.

However, excessive pumping results in the over exploitation of the groundwater (Laghari et al., 2012), and Pakistan is among those countries where groundwater extraction exceeds renewal rates. Major dependence on groundwater, resulting in lowering the water table, leads to a decline in surface water (Condon and Maxwell, 2019). Gigantic groundwater withdrawal (60 km^3) compared with lessen annual recharge (55 km^3) are posing serious threats of water scarcity annually (Giordano, 2009). Furthermore, environmental issues, decreasing water table, food security problem, and heavy economic cost are the serious appalling of excessive water withdrawal (Shah et al., 2001; Kijne, 1999; Kelleners and Chaudhry, 1998; Kahlowan and Azam, 2002; Khan et al., 2008; Famiglietti, 2014). The country is unable to cope with the rising irrigation requirements (Wada et al., 2010; Qureshi, 2015). Furthermore, surface water is inadequate to meet the irrigation needs of farmers. To fulfill the increasing demand of agricultural food, sustainable and efficient ways of agricultural production technologies are required using less available water (Lenton, 2014). Troy et al., 2015; Jägermeyr et al., 2017; Schauburger et al., 2017; Tack et al., 2017 propose that improving irrigation water in water scarce areas could lead to higher crop yields. Therefore, there is dire need to ascertain a special consideration regarding efficient use of water. Mostly studies highlighted the efficiencies of the various crops but the link between groundwater use efficiency and cropping pattern are hardly analyzed. Present research focuses on estimating the groundwater use efficiency of wheat-maize cropping pattern and accessing the various factors that affect technical and groundwater use efficiency in Bari doab.

MATERIALS AND METHODS

Study Area and Population

The study was conducted in Okara District, Punjab, Pakistan, which lies within the command area of the Lower Bari Doab Canal (LBDC) irrigation system. The LBDC is the second-largest canal irrigation system in Punjab, covering approximately 0.8 million hectares, of which nearly 595 thousand hectares are cultivated. The study area is situated between the Ravi and Beas rivers and is characterized by a mixed cropping system. Agriculture in the district is supported by both surface water and groundwater

irrigation; however, groundwater is the predominant source of irrigation for most farmers. Around 38,577 tube wells are operational in district, indicating the increasing dependence on groundwater resources for agricultural production. The study specifically focused on farmers located within the Depalpur distributary command area of Okara District.

Sampling Procedure and Sample Size

A two-stage random sampling technique was employed to select the study respondents. In the first stage, the Depalpur distributary was selected from the distributaries of Okara District using Geographic Information System (GIS) software with the assistance of the Punjab Irrigation Department (Fig.1). In the second stage, nine watercourses (10350-R, 17230-R, 21030-R, 112030-R, 112350-R, 11510-L, 69710-L, 69910-L, and 133280-L) were selected randomly from the command area of the Depalpur distributary. Subsequently, a

simple random sample of 214 farmers was selected from these watercourses to participate in the survey.

Data Collection

Primary data were collected using a structured and pre-tested questionnaire administered through the Open Data Kit (ODK) mobile application. Prior to the survey, the questionnaire was pretested and refined to improve its clarity, consistency, and relevance. Data were collected from farmers cultivating wheat during the Rabi season and maize during the Kharif season. Information regarding crop production, including yield, seed rate, land preparation (machine hours), labour use, fertilizer application, pesticide and herbicide use, irrigation practices, and other farm management variables were collected. These data were subsequently used to estimate technical efficiency and groundwater use efficiency among the sampled farmers.

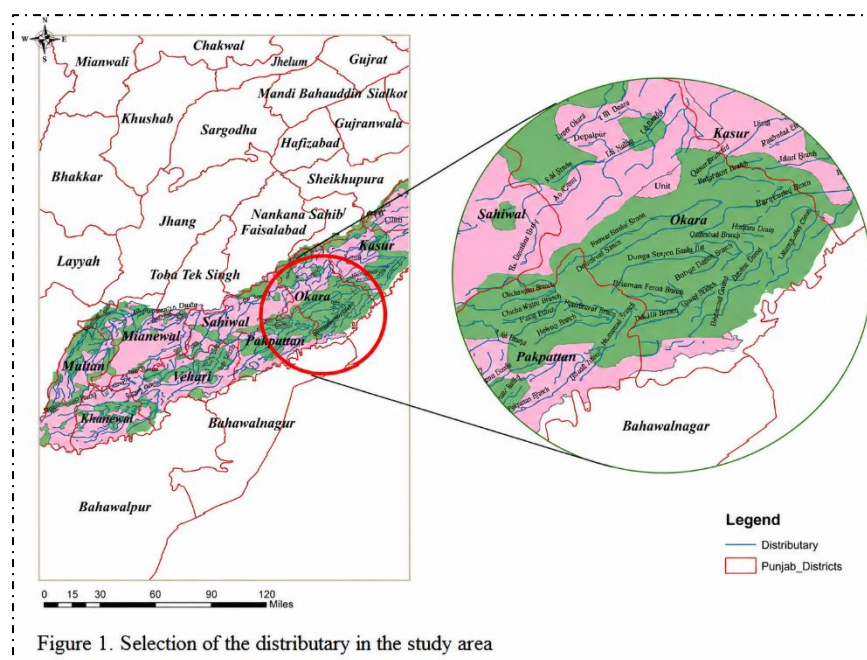


Figure 1. Selection of the distributary in the study area

Ethical Considerations

Ethical principles were strictly observed throughout the research process. Before data collection, the objectives and purpose of the study were clearly explained to all respondents, and informed verbal consent was obtained. Participation in the survey was entirely voluntary, and respondents were assured that they could withdraw from the interview at any stage without any consequences. The confidentiality and anonymity of the respondents were maintained by ensuring that personal information was not

disclosed or used for purposes other than academic research. The collected data were used solely for research purposes.

Data analysis

The collected data were checked for authenticity and analyzed using Statistical Package for Social Sciences (SPSS) software. Descriptive statistics, including frequencies, percentages, means, and standard deviations, were used to summarize the socioeconomic characteristics of the respondents and key farm-level variables. Groundwater

extracted quantity was calculated by a pretested estimated model in liters in lines with Eyhorn *et al.*, 2005, Watto 2015 and Mehmood 2024:

$$Q = \frac{t * 129574.1 * BHP}{[d + (255.5998 * BHP^2)/d^2 * D^4]}$$

Where:

Q: Volume of water in litres

t: Total irrigation time (hours)

BHP: Engine power

d: Bore Depth

D: Diameter of suction Pipe

Table 1 presents descriptive information used for estimation of Data Envelopment Analysis of wheat and maize. On an

average 3.9 acres of wheat and 10.11 acres of maize were cultivated. In the research area, significant variability in the sowing of both crops was observed. On average, wheat farmers used a seed rate of 50 kilograms and 8.70 kilograms for maize sowing in one acre. Compared with wheat, we witnessed higher number of machine hours operated and labor hours used for maize cultivation. Likewise, more fertilizer and chemicals doses were applied for maize than wheat crop. Approximately, 465 m³ groundwater was applied to wheat crop and nearly 990 m³ groundwater was used for maize cultivation. On an average 45.87 m³ per acre of produce was obtained from wheat crop and 58.03 m³ per acre yield was obtained from maize crop.

Table 1. Variables used for calculation of Data Envelopment Analysis.

Variable	Unit	Wheat				Maize			
		Mean	SD	Min	Max	Mean	SD	Min	Max
Crop area	Acres	3.9	1.61	1	7	10.11	15.3	0.8	200
Seed Rate	Kilogram per acre	50.48	2.94	40	60	8.70	0.77	5	10
Machine hours	hours per acre	3.92	1.61	1	7.8	4.28	1.49	1.0	10
Fertilizer	Kgs per acre	166.04	42.14	75	325	245	39.28	150	300
Chemicals	No.s per acre	0.94	0.76	0	3	3.80	0.51	3	5
Labour	Hours per acre	23.86	5.19	9.4	31.3	40.99	8.03	28.5	65.5
Irrigation water	m ³ per acre	465.11	145.7	136.6	972.4	990.85	737.8	179.3	3870
Yield	Monds per acre	45.87	5.03	24	55	58.03	8.71	35	80

Source: Author's own calculation

Theoretical Background

The terms Efficiency and Productivity are often used interchangeably, but they do not mean the same thing. Efficiency theory was based on "Brute Force" approach, which was used to solve difficult problem by considering each possible answer. In general, efficiency measures how effectively each resource, such as energy, time, space, etc., is utilized for its intended purpose or task (Yampolskiy, 2013). The efficiency of each Decision-Making Units (DMU) can be estimated through two techniques: firstly, Parametric; and secondly, Non-Parametric techniques. Stochastic Frontier Analysis estimation is conducted in parametric techniques, while Data Envelopment Analysis is used in Non-parametric techniques. In this study we employed nonparametric method to calculate efficiency because in this technique we can assess how much input is required to determine output level and how much input of each farm is reduced without disturbing output (Zhang *et al.*, 2014). Watto and Mugera, 2015 analyzed the different efficiencies

(economic, technical and allocative) for agriculture sector.

To observe the inputs and outputs of the farms in the groups specified by Banker *et al.*, 1984 for technical efficiency, the following linear programming equation was solved:

$$\text{Min}(\lambda\theta)\theta_{bo}$$

Subject to the constraint

$$\sum_{b=1}^n \lambda_b Y_b - Y_{bo} \geq 0$$

$$\sum_{b=1}^n \lambda_b X_{bo} - \theta X_{bo} \leq 0$$

$$\sum_{b=1}^n \lambda_b = 1 \dots \dots \lambda_b \geq 0$$

θ_{bo} is relative technical efficiency of the farmer. λ_b are the assigned weight as an input level farm denoting inefficient farm which needs to change into efficient one. Y_{bo} is output quantity of all the farms. X_{bo} is input quantity of all the Farms. $\sum_{b=1}^n \lambda_b$ is equation used to compute efficiency in variable return to scale.

Groundwater use efficiency

Sub-vector Efficiency Method or Slack-based approach is used to evaluate the efficiency of a single input. The input efficiency estimated by these methods involves non radial techniques but the Slack based Method provides not only slack variables but also efficiency scores. In line with Watto and Mugera, 2014; Asghar *et al.*, 2018 the present study also used the Slack based Method to calculate groundwater use efficiency for wheat and maize crops.

$$\text{Min}(\lambda, \theta, S^-, S^+)[\theta - \varepsilon(\sum_{b=1}^g S_b^- + \sum_{c=1}^k S_c^+)]$$

Subject to the constraint

$$\sum_{b=1}^n \lambda_b X_{bo} + S_b^- = \theta X_{bo}$$

$$\sum_{b=1}^n \lambda_b Y_b - S_b^- = Y_{co}$$

$$\sum_{b=1}^n \lambda_b = 1 \dots \dots \lambda_b \geq 0$$

Where S^- denotes the extreme value of the input, S^+ represents potential achievable output. ε is a positive and real number. Estimation of minimization problem explains farmer is attaining full efficiency level if all the slack are zero and $\theta = 1$. If $\theta = 1$, all other slacks are non zero than farm is weakly efficient.

Groundwater use efficiency, as calculated by Watto and Mugera, 2015, is defined as the proportion of actual irrigation water utilized by a crop relative to the total quantity of irrigation water supplied to the crop.

$$GWE = \frac{Q_u}{Q_g} * 100$$

Where GWE is groundwater efficiency, Q_u is the groundwater used by a crop (acre-inches) and Q_g is total quantity of groundwater applied.

Tobit Model (Bootstrap Truncated Model)

In regression analysis, Tobit models are used specifically to address regression models that involve censored variable (Wooldridge, 2010) where explained variable is considered in a restricted way (Wang *et al.*, 2017). Many researchers (Xiong *et al.*, 2019; Yu *et al.*, 2019; Yang and Wei, 2019) used Tobit analysis to estimate industrial efficiency, energy efficiency. Data Envelopment Analysis estimates total input efficiency with incorporating production function of decision making units (Wu *et al.*, 2014). Efficiency scores are

considered as censored variable having values in between zero and one. According to McDonald, 2009, efficiency estimated values are fractional digits that range between zero and one which may experience serial correlation or heteroscedasticity in liner regression or Tobit analysis (Kieschnick and McCullough, 2003). Due to the deficiency of statistical characteristics of some parameters, the feasibility of outcomes is questionable in traditional DEA. Simar and Wilson, 2002 developed Bootstrap DEA from traditional DEA after using empirical data. This improvement correctly specified the deviation in confidence interval (Wang *et al.*, 2020). Second stage bootstrap truncated model gives more consistent results. Following is the model use for the Tobit regression analysis.

$$Y_{GWE} = \alpha_h + \sum_{h=1}^n \beta_h Z_h + \varepsilon_h \text{ for } h = 1, \dots, N$$

Y_{GWE} = Groundwater Efficiency of hth farm.

Z_h = Set of explanatory variables

ε_h = Error term

RESULTS

Technical and Groundwater Use Efficiency of Wheat and Maize

Table 2 presents the frequency distribution and summary statistics of technical efficiency (TE) and groundwater use efficiency (GWE) for wheat maize cropping pattern under variable returns to scale. The mean technical efficiency for wheat was 0.94, and for maize it was 0.92, indicating that farmers operated close to the production frontier. Technical efficiency ranged from 0.73 to 1.00 for wheat and 0.76 to 1.00 for maize crop.

Approximately 20 percent of wheat and 42 percent of maize growers achieved full technical efficiency (TE = 1), whereas only 6 percent of wheat and 8 percent of maize farmers were technically inefficient. Groundwater use efficiency was substantially lower than technical efficiency for both crops. The average groundwater use efficiency was 0.63 for wheat and 0.64 for maize, with values ranging from 0.27 to 1.00 and 0.20 to 1.00, respectively. Only 19 percent of wheat growers and 28 percent of maize growers achieved full groundwater use efficiency (GWE = 1), indicating considerable scope for improving groundwater utilization without reducing crop output.

Table 2. Frequency distribution of Groundwater use Efficiency.

Farm Location	Technical Efficiency		Groundwater use Efficiency	
	Wheat	Maize	Wheat	Maize
<30	0	0	07	17
30-39	0	0	32	43
40-49	0	0	30	33
50-59	0	0	37	23
60-69	0	0	35	12
70-79	2	13	22	13
80-89	39	76	5	6
90-99	130	34	5	5
100	43	91	41	62
Mean	0.94	0.92	0.63	0.64
SD	0.04	0.08	0.22	0.28
Min	0.73	0.76	0.27	0.2
Max	1	1	1	1

Source: Author's own calculation

Correlation between Technical Efficiency and Groundwater Use Efficiency

The Spearman rank correlation coefficients between technical efficiency and groundwater use efficiency are presented in Table 3. The correlation coefficient was

0.533 for wheat and 0.613 for maize, indicating a moderate to strong positive association between the two efficiency measures. Farmers exhibiting higher technical efficiency also tended to use groundwater more efficiently.

Table 3. The Spearman's rank correlation between technical efficiency and groundwater use efficiency.

Variable	Technical Efficiency (Wheat)	Groundwater use efficiency (Wheat)	Variable	Technical Efficiency (Maize)	Groundwater use efficiency (Maize)
Technical Efficiency (Wheat)	1.00	0.533	Technical Efficiency (Maize)	1.00	0.613
Groundwater use efficiency (Wheat)	0.533	1.00	Groundwater use efficiency (Maize)	0.613	1.00

Source: Author's own calculation

Determinants of Technical and Groundwater Use Efficiency

The bootstrap Tobit estimation results are presented in Table 4. Education significantly improved the technical efficiency of wheat production but had no statistically significant effect on maize production. Farming experience positively influenced the technical efficiency of wheat growers, whereas its effect on maize efficiency was insignificant.

Family size negatively affected technical efficiency in both wheat and maize production and also reduced groundwater use efficiency in maize. Land ownership

had a significant negative effect on wheat technical efficiency but was insignificant for maize.

Extension training significantly increased groundwater use efficiency in wheat production. Watercourse distance negatively affected both technical and groundwater use efficiency, particularly in maize. Tube-well ownership significantly improved technical efficiency and groundwater use efficiency among maize farmers. Declining groundwater levels reduced wheat technical efficiency, while suitable groundwater quality significantly improved wheat technical efficiency but negatively influenced groundwater use efficiency.

Table 4. Tobit Analysis.

C	Technical Efficiency				Groundwater use Efficiency			
	Wheat		Maize		Wheat		Maize	
	Coefficient	SE	Coefficient	SE	Coefficient	SE	Coefficient	SE
	0.946	0.0101	0.9671	0.0304	0.7053	0.0786	0.6707	0.1150
Education	0.001**	0.0004	0.0008	0.0012	0.0043	0.0031	0.0009	0.0045
Experience	0.0005***	0.0001	0.0005	0.0004	0.0007	0.0010	0.0004	0.0015
Family Size	-0.0015***	0.0004	-0.0031***	0.0012	-0.0034	0.0030	-0.0066**	0.0045
Ownership of land (1=owner, 0=tennants)	-0.0138***	0.0043	0.0069	0.0128	-0.0013	0.0330	0.0288	0.0488
Extension Training	0.0339	0.0039	0.0108	0.0118	0.1278***	0.0304	0.0494	0.0445
Watercouse distance (km)	-0.0089	0.0009	-0.0069**	0.0027	-0.0346***	0.0071	-0.0163**	0.0104
Tubewell Ownership (1=yes, no=0)	0.0024	0.0037	0.0425***	0.0111	0.0274	0.0288	0.1570***	0.0424
Lined Watercouse (1=yes, no=0)	-0.0074*	0.0038	-0.0001	0.0115	0.0098	0.0297	0.0199	0.0435
Declining GW (1=yes, no=0)	-0.0116***	0.0040	-0.0112	0.0119	-0.0136	0.0309	0.0161	0.0453
Sub soil water (Fit=1, unfit=0)	0.0149***	0.0061	-0.0376**	0.0182	-0.0798**	0.0472	-0.0955	0.0691
Log Likelihood	481.6		247.1		48.48		16.01	

Source: Author's own calculation.

DISCUSSION

The high technical efficiency estimates indicate that wheat and maize farmers in the study area are generally operating close to the production frontier. Nevertheless, the lower groundwater use efficiency suggests that substantial water savings are achievable without compromising crop yields. This finding implies that improving irrigation management practices could contribute significantly to groundwater conservation while maintaining agricultural productivity.

The average technical efficiency estimates obtained in this study are considerably higher than those reported by Salam and Hameed (2022), who estimated technical efficiency scores ranging from 0.61 to 0.80 for wheat production across different agro-ecological zones of Punjab. Similarly, the present findings indicate relatively higher efficiency than those reported by Alam et al. (2020) for maize producers in Gilgit-Baltistan, although they are broadly comparable with the findings of Shah et al. (2020) for maize growers in Khyber Pakhtunkhwa.

The relatively low groundwater use efficiency highlights the importance of promoting water-saving irrigation technologies and improved irrigation scheduling. Similar

levels of irrigation efficiency were reported by Watto and Mugera (2019), who observed irrigation efficiency scores of 0.66–0.67 among wheat producers in Punjab.

The positive relationship between technical efficiency and groundwater use efficiency indicates that improvements in farm management practices are likely to enhance both production performance and water conservation simultaneously. The Tobit estimates further demonstrate that farmers' education and farming experience contribute positively to technical efficiency by improving managerial capacity and production decisions. These findings are consistent with Xu et al. (2015), Ayele et al. (2019), Abate et al. (2019), Dessale (2019), Lubadde et al. (2016), and Mahmood et al. (2020). The negative relationship of family size may reflect higher dependency ratios and inefficient allocation of household labour, supporting the findings of Mussá et al. (2015) and Babatunde and Qaim (2010). In contrast, previous studies by Bridges et al. (2013) and Weltin et al. (2017) argued that larger households may enhance farm performance through greater labour availability. The positive impact of extension services on groundwater use efficiency confirms the importance of

agricultural advisory services in disseminating improved irrigation and crop management practices, corroborating the findings of Alwarritzi et al. (2015) and Tenaye (2020). The negative effect of watercourse distance suggests that conveyance losses reduce irrigation efficiency, while the positive influence of tube-well ownership reflects the benefits of timely and reliable access to irrigation water. Finally, farmers' perceptions regarding declining groundwater levels indicate increasing awareness of groundwater depletion, emphasizing the need for policies promoting sustainable groundwater management.

CONCLUSION

The estimations suggested that wheat and maize cropping operated at higher level of technical efficiency (0.94 & 0.92 respectively) than groundwater use efficiency scores (0.63 & 0.64 respectively). The mean technical efficiency score of wheat farms was 0.94 and for maize, TE was 0.92. Considerable difference was observed in groundwater use inefficiency in wheat maize cropping pattern. On an average groundwater use efficiency of wheat farms was 0.63, with a range between 0.27 and 1, and for maize, it was estimated as 0.64, ranging from 0.17 to 1. The results indicated that wheat farms can reduce 37 percent groundwater use and maize farms can reduce 36 percent irrigation water application to save 0.11 million m³ during one calendar year. Tobit analysis indicated that improving education status of farmers, higher level of farmer experience enhancement of agricultural extension services and entitlement of tube well to an individual would result in achieving higher level of technical and groundwater use efficiencies. Construction of watercourses and their maintenance plays a pivotal role in farm policy making to attain sustainability in using groundwater. Based on outcomes from the research indicated that despite of availability of lined watercourses, poor maintenance resulted in reducing technical efficiency of farms.

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