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# Exploring competitiveness of surface water versus ground water irrigation and their impacts on rice productivity and efficiency: An empirical analysis from Bangladesh

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A R T I C L E I N F O

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A B S T R A C T

The choice of irrigation water sources is crucial in rice farming as water availability and cost can vary across water sources. Groundwater caters three-quarters of the total irrigated land in Bangladesh, where rice area alone occupies 80% of the total irrigated land. The present study compares productivity and efficiency differences and determinants of surface and groundwater irrigation users based on a sample of 6947 dry-winter rice growing plots from the nationally representative Bangladesh Integrated Household Survey-2018 database. A range of methods was adopted to correct for heterogeneity in irrigation water source choice decision, self-selection and observable biases. This involved an estimation of a Stochastic Production Frontier (SPF) model with the pooled sample first, then an application of Propensity Score Matching (PSM) to remove self-selection and observable biases, then a test of heterogeneity in irrigation source choices was conducted, and finally estimated two SPF separately for matched samples of groundwater and surface water irrigation users. Results revealed a robust effect of groundwater irrigation in enhancing rice productivity and efficiency. Seed and its quality, fertilizer and soil type are also significant drivers of rice productivity. The significant drivers of efficiency are plot ownership, irrigation frequency, subsidy and family size. Large farms with groundwater-irrigated plots are relatively more efficient. Significantly lower efficiency exists in areas vulnerable to drought. These results raise sustainability concerns owing to the high level of groundwater extraction and falling water table. Policymakers need to devise innovative strategies to increase use of surface water irrigation without sacrificing productivity and efficiency, which has been a priority policy drive in Bangladesh.

## 1. Introduction

Many developing countries, including Bangladesh, have followed the cereal-based Green Revolution (GR) technology path since 1960 s and were successful in coping with 'food-population' imbalance (Khush, 2001). But despite GR's significant impact on food production and socio-economic development in developing economies, a notable portion of the global population still lives with hunger and nutritional insecurity (Pingali, 2012). Moreover, there are rising environmental concerns regarding biodiversity loss, greenhouse gas emissions, and reduced availability of fertile soils and clean water amidst widespread adoption of GR technologies in food production across the globe (Foley et al., 2005; Tyagi, 2016). During the last four decades, there have been reduced returns from different inputs, which was (Singh, 2000) termed as a "high input-use and decelerating productivity" growth phase for Indian agriculture. In the future, more challenges are anticipated as the global food demand in 2050 will double compared to that of 2010 (Godfray et al., 2010). This increased demand will be accompanied by increasing competition for land, water and energy as both population and size of the economies are growing (OECD, 2012). The existing groundwater-based irrigation system raises severe sustainability concern, since demand for water beyond agriculture will also rise substantially (CSIRO, 2014). Meanwhile, the impacts of climate change have reached critical tipping points (Masson-Delmotte et al., 2021) along with an accelerating concern about the loss of global biodiversity due to exploitation, pollution and habitat destruction from the

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conversion of unmanaged land for food production (OECD, 2012). Hence, increasing productivity of finite resources, such as land and water, through the adoption of productivity enhancing technologies are important to address future challenges of food production (Pingali, 2012).

Along with varietal improvements, chemical inputs and modern management practices, irrigation was another important component of the GR package. Groundwater irrigation, especially the adoption of shallow tube-wells during the dry season, has played an undisputed role in the growth of the crop sector (CSIRO, 2014). The country's irrigated land increased from 7056 to 7685 thousand hectares from 2011 to 2018 (BBS, 2021). Currently in the country, around 93% of the total water demand comes from agriculture of which more than 80% is met from groundwater (CSIRO, 2014; WRG, 2021). Over the years, there has been a gradual decline in the surface water irrigation area (Fig. 1). In Bangladesh around 1.43 million and 0.32 million irrigation pumps are operated by diesel and electricity, respectively, and they annually emit around 7 million tons of carbon dioxide (Islam et al., 2017), whereas groundwater overexploitation has led to depletion of groundwater, estimated to be in the range of − 0.5 to − 0.8 $km^3$/year between 2003 and 2007, which accelerated in recent years and is more severe in water stressed regions (Shamsudduha et al., 2012; Rahman and Mahbub, 2012). In the water stressed northern districts, the groundwater table in a period of one year (2015–2016) has dropped by 15% (Fig. 2) while the geology of the area is no longer suitable for extensive exploitation of groundwater (Asad-uz-Zaman and Rushton, 2006; Shahid and Hazarika, 2010). Deeper groundwater extraction increases irrigation costs and ultimately affects the livelihoods of farmers. The stress is more for those dependent on groundwater, particularly in the absence of appropriate adaptation measures (Dey et al., 2013). It is noteworthy to mention that compared to other countries in the Indo-Gangetic region, Bangladesh has lower irrigation efficiency and higher irrigation costs (WRG, 2021). Overexploitation, changes in land use and cropping patterns, upstream river flow and reduction in wetland areas, all contribute to groundwater decline (Rahman et al., 2021). Thus, a substantial concern remains regarding the sustainability of groundwater-dependent farming systems.

Given such challenges, surface water irrigation is prescribed, particularly to counter problems resulting from groundwater overexploitation. The Bangladesh government has prioritized surface water irrigation and documented this in several policy documents, but there has been a concern as to whether surface water availability is sufficient to fulfill the irrigation requirement needed to produce and meet continuously increasing food demand (Watto and Mugera, 2015).

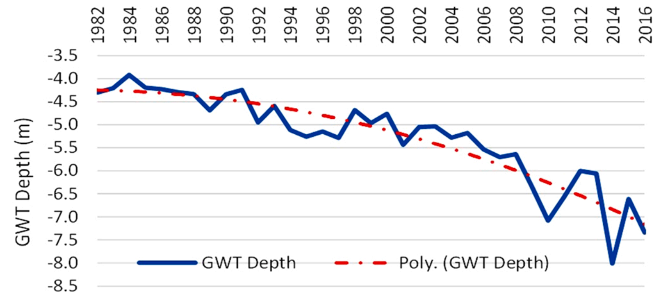


**Fig. 2.** Groundwater table (GWT) depth in Northern Bangladesh.
Source: FPMU Food Security Monitoring Report, Ministry of Food.

Importantly, Bangladesh has a skewed distribution of rainfall as well as availability of surface water during the year (Mukherjee et al., 2015). Despite this policy thrust, surface water in Bangladesh supplies only one-fourth of the country's total irrigated area (FPMU, 2021). On the contrary, compared to that of 1982/83, the proportion of groundwater-irrigated area:total area doubled (BADC, 2020). In 2019/20, surface water area was estimated to be 30.05 thousand hectares, which is an increase of only 1.76 thousand hectares from its 2018/19 level but effectively a significant reduction from the level observed in 2017/18 (FPMU, 2021). Bangladesh made massive investments in the form of re-excavating canals, setting up dams, and installing pumps for ensuring availability of surface water for irrigation (Alam, 2015; FPMU, 2021). However, the desired expansion in its coverage for irrigation remains low. Actual adoption of any particular technology is subject to several factors including farmers' socio-economic circumstances and technology domain and protection of the environment may not be always a farmer's prime concern, particularly since GR technology has motivated and trained farmers to use groundwater for irrigation for decades. The trend is quite unlikely to change in the foreseeable future. The government is trying to work out a solution by diverting the need for supplementary irrigation from groundwater sources to surface water while ensuring that productivity of crop and total food-grain production are not adversely affected and continues to improve instead.

Given these challenges, it is necessary to judge the merit of the choice of irrigation water source in rice production by farmers and its impact on productivity and efficiency using an in-depth analysis at a large scale, e.g., a nationally representative sample from Bangladesh. The specific objectives of this study are to: (a) estimate the share of cropped area

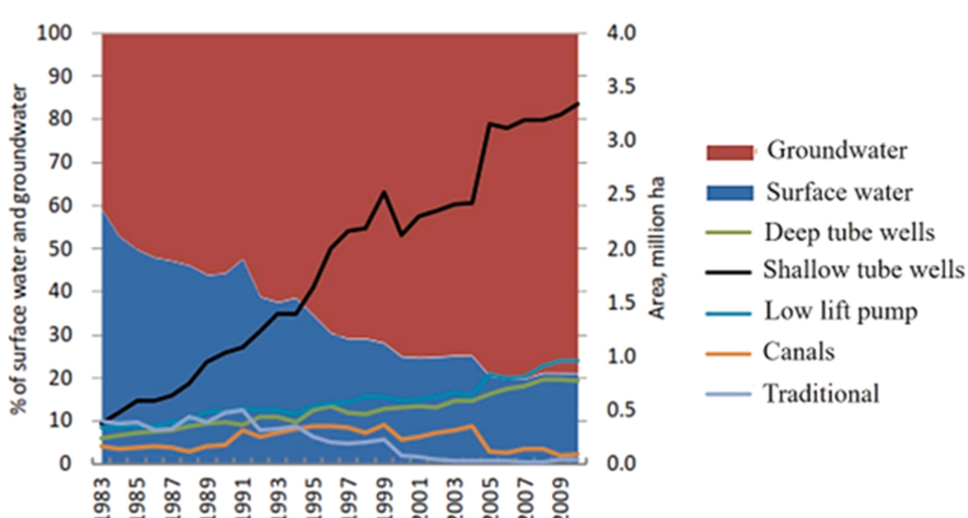


**Fig. 1.** Area irrigated by different irrigation methods and sources of water.
Source: CSIRO (2014).

irrigated by surface and ground water sources at the plot level; (b) determine the range of socio-economic factors influencing a farmer's irrigation water source decision, (c) determine the impact of the chosen irrigation water source on crop productivity; and (d) estimate production efficiency of the chosen irrigation source by farmers.

We chose rice because it is the second most produced and staple crop consumed by approximately 50% of the global population (FAO, 1947). In Bangladesh, rice is the major staple grown in 80% of the total cultivable land. Also, the Boro season (dry winter) rice, which provides the bulk of total foodgrain production of the country, is highly dependent on supplementary irrigation which has been met by mainly groundwater sources for decades.

Our work enriches the existing pool of knowledge in multiple ways. First, we explicitly considered the issue of heterogeneity in irrigation water source choice and subsequently tested its existence. Second, we also accounted for self-selection and observable biases arising from the choice of irrigation source so that the net effect of the merit of chosen source (i.e., albeit surface water or groundwater) by farmers on crop productivity and efficiency can be confirmed. Third, we used a large number of plot level data which is a more specific source and most suitable to address the stated research objectives with authenticity and validity. Fourth, we have utilized a large number of samples from a nationally representative Bangladesh Integrated Household Survey (BIHS) which makes our results not only generalizable for Bangladesh, but also for a wider range of economies with similar agricultural sectors characterized by widespread use of irrigation methods and socio-economic circumstances. And fifth, we explicitly analyzed both surface and ground water source for irrigation in details which is usually ignored in Bangladesh-focused literature (CSIRO, 2014; Rahman et al., 2021).

## 2. Materials and methods

### 2.1. The data

This study uses International Food Policy Research Institute's (IFPRI) BIHS 18–19 database which is representative of rural Bangladesh as a whole. The database contains information on 9143 households belonging to 325 Primary Sampling Units (PSU) from seven administrative divisions of Bangladesh, which were selected through a two-stage stratified sampling procedure using the sampling frame based on the national population census (the detailed sampling procedure is available at: https://www.ifpri.org/publication/bangladesh-integrated-household-survey-bihs-2018–2019).

Among the surveyed households, 4262 cultivated rice in 16,868 plots during December 2017 to November 2018. We considered only plots growing dry winter rice since the season supplies more than half (53.7%) of the country's annual rice production (BBS, 2021), and groundwater is the dominant water source in the season. In other seasons, rice farming mainly depends on natural rainfall and only provides supplementary irrigation when rainfall is inadequate.

Among the plots growing dry winter rice, 1570 were irrigated by surface water, and 5377 were irrigated by groundwater. Finally, after applying the Propensity Score Matching (PSM) technique, we could match 1108 households (699 surface water and 409 groundwater) who cultivated rice in 3140 plots (1570 surface water and 1570 groundwater) for our analysis.

### 2.2. Measuring productivity and efficiency of irrigation sources – the Stochastic Frontier Analysis

Following Mayen et al. (2010) and Anang et al. (2017), the Stochastic Production Frontier (SPF) function that incorporates both the stochastic and technical inefficiency effects in the frontier as functions of observable variables can be expressed as:

$$\ln Q_i = \boldsymbol{X_i\beta} + v_i - u_i \tag{1}$$

where $Q_i$ is the observed rice yield by the $i^{th}$ plot ($i = 1,2,3,4,5,\ldots,N$); $\boldsymbol{X_i}$ denotes the inputs vector that applied in the $i^{th}$ plot; and $\boldsymbol{\beta}$ indicate the vector of the parameters to be estimated using the Maximum Likelihood Estimation (MLE) technique. The error $v_i$ is the statistical noise that is identically and independently distributed, i.e. $iid \sim N(0, \sigma_v^2)$. The non-negative and half-normally distributed stochastic error term denoted by $u_i \sim N^+(0, \sigma_u^2)$ represents technical inefficiency in production. Table 1 shows a detailed description of both the production and efficiency explaining variables along with their measurement procedures. Both the stochastic terms are uncorrelated with each other. The proportion of the variance is explained by inefficiency, $\lambda_i = \sigma_{ui}^2/\sigma_{vi}^2$ (Battese and Coelli, 1995). The density function for $\varepsilon_i \equiv v_i - u_i = \ln Q_i - \boldsymbol{X_i\beta}$ is

$$f_i(\varepsilon_i) = (2/\sigma_i)\phi(\varepsilon_i/\sigma_i)(1 - \Phi(\lambda_i\varepsilon_i/\sigma_i)), \text{for} - \infty < \varepsilon_i < +\infty \tag{2}$$

where, $\phi$ indicates the standard normal density function and $\Phi$ denotes the standard normal cumulative distribution function. The technical efficiency (TE) is calculated by the ratio of observed yield to the corresponding stochastic frontier yield and can be estimated as:

$$TE_i = \frac{Q_i}{\exp(\boldsymbol{X_i\beta} + v_i)} = \frac{\exp(\boldsymbol{X_i\beta} + v_i - u_i)}{\exp(\boldsymbol{X_i\beta} + v_i)} = \exp(-u_i), \text{where} 0 \le TE \le 1 \tag{3}$$

Table 2 briefly presents the analytical techniques followed in the study.

### 2.3. Self-selection into farmer's decision to choose irrigation source

Homogenous technology across farms is an assumption required while estimating a production function (Elias et al., 2013). However, heterogeneity may exist across farms as some use surface water for irrigation while others do not. As has already been mentioned, we suspect that the production frontiers between surface and groundwater irrigated farms may vary as there are potential self-selection issues into irrigation source choices, and the environmental or biophysical conditions apply restrictions on production. Gebregziabher et al. (2012) stated that since biophysical settings affect production by impacting farming decisions, it is necessary to consider the differences in surrounding environmental settings between farms, otherwise the estimated results might be biased. We, therefore, perform a formal test with the assumption of homogeneous production technology by allowing production technologies to vary between surface and groundwater irrigated plots by including a dummy variable for groundwater irrigation source that interacts with the conventional input vector in the production function (Elias et al., 2013). Following Ahmed and Melesse (2018), we have performed a Likelihood Ratio (LR) test and rejected the null hypothesis of farms using homogenous technology for the PSM subsamples ($LR = 268.41, \chi^2 = 43.70, df = 25$), which confirms that the two groups use different technologies and therefore require separate SPF models to be estimated for each group.

Some earlier studies used SPF approach for comparing differences in TE between the participants and non-participants of a program or intervention, where the endogeneity problem was addressed by following Heckman's two-step approach. However, this approach is less applicable when nonlinear models like SPF are employed (Elias et al., 2013). Following Bravo-Ureta et al. (2020), Elias et al. (2013), and Mayen et al. (2010), we have employed the propensity score matching (PSM) technique and estimated the technical efficiency of groundwater and surface water irrigated plots separately on the matched sample. Mayen et al. (2010) noted that matching models generate experiments that permit for random assignment of the production type (groundwater versus surface water irrigation) and consequently, allow a direct linking between groundwater irrigation and TE.

**Table 1**
Summary statistics of the variables used in the study.

| Variables | Description of variables | Surface water irrigation | Groundwater irrigation (Unmatched[a]) | Groundwater irrigation (Matched[b]) |
|---|---|---|---|---|
| Output variable | | | | |
| Yield | Rice output (kg/ha) | 5559.5 | 5933.4*** | 5858.5*** |
| Input variables | | | | |
| Labor | Sum of family and hired labor (hours/ha) | 873.07 | 837.30*** | 858.93 |
| Fertilizer | Cost[c] of all types of chemical fertilizer (USD/ha) | 112.62 | 150.72*** | 142.90*** |
| Irrigation | Cost of irrigation (USD/ha) | 135.40 | 207.17*** | 210.81*** |
| Seed | Cost of home and market supplied seed (USD/ha) | 118.83 | 99.94*** | 111.59*** |
| Other inputs | Cost for pesticides, rental machineries and draft animals (USD/ha) | 110.87 | 116.08*** | 110.39 |
| Rice variety (Base = High yielding variety (HYV)) | | | | |
| HYV | 1 if HYV variety is cultivated in the plot, 0 otherwise | 0.634 | 0.887*** | 0.799*** |
| Hybrid | 1 if hybrid variety is cultivated in the plot, 0 otherwise | 0.366 | 0.113*** | 0.201*** |
| Soil type (Base = Sandy-loam soil) | | | | |
| Sandy-loam | 1 if the plot soil type is sandy-loam, 0 otherwise | 0.159 | 0.219*** | 0.180 |
| Clay | 1 if the plot soil type is clay, 0 otherwise | 0.038 | 0.017*** | 0.063*** |
| Loam | 1 if the plot soil type is loam, 0 otherwise | 0.173 | 0.184 | 0.189 |
| Sandy | 1 if the plot soil type is sandy, 0 otherwise | 0.041 | 0.043 | 0.026** |
| Clay loam | 1 if the plot soil type is clay-loam, 0 otherwise | 0.590 | 0.537*** | 0.542*** |
| Inefficiency explaining variables | | | | |
| Farm size dummy (Base= large farms) | | | | |
| Landless | 1 if the farmer is landless, 0 otherwise | 0.061 | 0.115*** | 0.102*** |
| Marginal | 1 if the farmer is marginal, 0 otherwise | 0.199 | 0.257*** | 0.243*** |
| Small | 1 if the farmer is small, 0 otherwise | 0.469 | 0.431*** | 0.387*** |
| Medium | 1 if the farmer is medium, 0 otherwise | 0.204 | 0.170*** | 0.180* |
| Large | 1 if the farmer is large, 0 otherwise | 0.066 | 0.027*** | 0.088** |
| Age | Age of the household head (years) | 49.60 | 48.30*** | 49.60 |
| Education | Years of formal schooling completed by the household head | 3.989 | 3.863 | 3.989 |
| Family size | Number of persons in the household (no) | 6.362 | 5.356*** | 6.362 |
| Subsidy card | Dummy; 1 if the household has a subsidy card, 0 otherwise | 0.283 | 0.235*** | 0.290 |
| Land parcel | Number of plots | 9.155 | 9.684*** | 8.836* |
| Irrigation number | Total number of irrigation events during dry winter rice production in the plot (no) | 13.79 | 27.31*** | 27.54*** |
| Extension service | Dummy; 1 if the extension worker visited the plot during 2018-19; 0 otherwise | 0.093 | 0.171*** | 0.093 |
| Own plot | Dummy; 1 if the household is the plot owner, 0 otherwise | 0.290 | 0.313* | 0.281 |
| Off-farm income | Total annual off-farm income of the household (USD) | 1899.5 | 1994.1** | 1988.3 |
| Drought risk | Dummy; 1 if the household faced drought risk in the dry-winter season, 0 otherwise | 0.138 | 0.453*** | 0.138 |
| Regional dummy (Base = northern region) | | | | |
| Southern | 1 if the farm is located in the southern region, 0 otherwise | 0.527 | 0.381*** | 0.527 |
| Additional variables for the probit model | | | | |
| Farm size | Total land (ha) | 0.881 | 0.699*** | 0.881 |
| Machinery owner | Dummy; 1 if the household owns an irrigation machine, 0 otherwise | 0.175 | 0.204*** | 0.175 |
| Energy dummy (Base = Electricity) | | | | |
| Manual irrigation | 1 if the farm used manual for irrigation, 0 otherwise | 0.129 | 0.003*** | 0.129 |
| Diesel | 1 if the farm used diesel for irrigation, 0 otherwise | 0.728 | 0.479*** | 0.728 |
| Electricity | 1 if the farm used electricity for irrigation; 0 otherwise | 0.143 | 0.518*** | 0.143 |
| Consumption and selling | Dummy; 1 if the household cultivated rice for both consumption and selling purposes, 0 otherwise | 0.654 | 0.768*** | 0.654 |
| Wage work | Dummy; 1 if the household head is day labor, 0 otherwise | 0.218 | 0.240* | 0.175*** |
| Agricultural cooperative membership | Dummy; 1 if the household head is a member of an agricultural cooperative, 0 otherwise | 0.147 | 0.114*** | 0.101*** |
| Flood depth | Usual flood depth (during monsoon/flood season) at the plot (feet) | 4.417 | 1.949*** | 4.417 |
| Sample size | | 1570 | 5377 | 1570 |

Note: [1] Following Department of Agricultural Extension (DAE) the farmers were classified as: landless (upto 0.202 hectare of land), marginal (0.203 to 0.405hectares of land), small (0.406 to 1.012 hectares of land), medium (1.013 to 2.024 hectares of land) and large (more than 2.024 hectares of land).
***, **, and * indicate mean differences between surface water and groundwater irrigation are significant at 1%, 5%, 10% level, respectively. Figures in parenthesis are standard deviations.
[a] The groundwater irrigated plots before PSM
[b] The groundwater irrigated plots after PSM, i.e. the counterfactual group
[c] All costs and values are converted at US dollars (One Bangladeshi taka is approximately equal to 0.012 US dollars)

Again, the production frontier and parameters of the production function $\boldsymbol{\beta s}$ differ between the groundwater and surface water irrigated plots due to restrictions on the production process executed by the groundwater irrigated farmers. It also comprises the indicator variable for groundwater irrigation that relates to the input vector$\boldsymbol{X_i}$. The farmers who use surface water irrigation generate a propensity $P_i^*$, a model based on observable characteristics $(\boldsymbol{M_i})$ and can be expressed as follows:

$$P_i^* = \boldsymbol{M_i}\boldsymbol{\alpha} + \delta_i \tag{4}$$

where α represents unknown parameters to be estimated and $\delta_i$ is a random disturbance term. When the variables in the selection model $(\boldsymbol{M_i})$ impact rice productivity and we fail to include them in Eq. (1), the self-selection indicator variable in Eq. (1) becomes correlated with the error $\varepsilon_i$ (Eq. 2). Consequently, our estimated **βs** become biased as there is endogeneity resulting from the farmer's surface water irrigation decision.

Though it is argued that PSM may not be an appropriate technique if unobserved variables affect the outcome variable (Ahmed and Melesse, 2018; Khonje et al., 2015), particularly when the undetected variables may affect surface water choice but are not considered directly (Mayen et al., 2010), we assume that the distributions of such undetected variables are the same between the groups (e.g. Mayen et al., 2010).

Furthermore, following Villano et al. (2015) and Salam et al. (2021), the balancing property was tested to ensure that the samples within the common support area have the same distribution of observable characteristics, irrespective of irrigation water sources. The Average Treatment Effect on the Treated (ATET) is computed by matching[1] each surface water irrigated plot with the groundwater irrigated plot having closest propensity scores. The ATET is estimated as:

$$ATET = E(Q_1|S = 1) - E(Q_0|S = 0) \tag{5}$$

where $S_1$ and $S_0$ are rice yield from groundwater and surface water irrigated plots, respectively. The dummy variable denoted by $S$ equals to 1 for farmers using groundwater for irrigation, and otherwise zero.

## 3. Results and discussion

### 3.1. Proportion of plot and area under surface and groundwater irrigation

A total of 77.4% of plots occupying 75.77% of total paddy area in the dry winter season were irrigated using groundwater, whereas the remaining plots and area were irrigated by surface water (Table 3) thereby reflecting the dominant role of groundwater as the main irrigation source to produce rice in Bangladesh.

### 3.2. Summary statistics

Summary statistics of the variables used in the econometric analysis are presented in Table 1. The number of variables with a significant difference between the two groups was reduced after matching samples, i.e. after PSM, variances in the mentioned variables between groups were reduced.

Compared to the surface water-irrigated plots, yield in groundwater-irrigated plots is 6.7% and 5.4% higher for the unmatched and matched sample, respectively. In the group of the matched sample, the groundwater-irrigated plots use 1.62% and 6.09% less labor and seed, but pay 26.9% higher fertilizer cost, compared to the plots irrigated by surface water. Number of irrigations applied in groundwater-irrigated plots is around 1.5 times higher than that of surface water irrigated plot, while the associated cost is almost double in case of groundwater irrigated plots.

In accordance with the National Statistics (BBS, 2021), more than 70% of farmers own less than 1 hectare of land. In case of the unmatched sample, relatively higher proportion of plots in the southern region used surface water because of the abundance of open and close water bodies in the region (WRG, 2021).

### 3.3. Finding a proper counterfactual group for groundwater users

#### 3.3.1. Econometric analysis for correcting self-selection bias

First, we checked whether there is self-selection bias for groundwater irrigation choice. For this purpose, Durbin-Wu-Hausman (DWH) test is conducted to identify whether the dummy for groundwater in equation (7) is endogenous. The test is conducted through estimating equation (6) as a linear probability model and rejects the null hypothesis that farmer's groundwater irrigation choice decision is exogenous (Table 5).

#### 3.3.2. Determinants of irrigation water source choice decision

Table 4 shows that among the fourteen explanatory variables used in the probit model, twelve have a significant role in explaining farmers' irrigation water source choice decision. The farmers who experienced drought risk in the dry winter season are less likely to irrigate their plots with surface water than their counterparts who did not face the risk. This is because average rainfall is low in the drought-affected region, especially in winter season, which depletes the amount and source of surface water (Prodhan et al., 2020).

Compared to the northern region, plots located in southern region have higher probability to be irrigated with surface water. The southern region has more availability of water bodies, which increases the probability of using surface water (Krupnik et al., 2017). The Bangladesh government has also emphasized shifting to less-costly surface water irrigation from highly subsidized and energy-intensive groundwater irrigation in southern Bangladesh (MoA and FAO, 2013). Plots with higher flood depth are likely to have nearby water sources and hence are more likely to utilize the available surface water for irrigation.

Members of agricultural cooperatives are more likely to adopt surface water irrigation. Having nearby surface water sources can motivate

**Table 2**
Estimation steps.

| Step No. | Action | Outcome | Limitations and improvements |
|---|---|---|---|
| 1. | We run a pooled unmatched SPF model with the dummy for the choice of groundwater (1 for groundwater irrigation, 0 otherwise) by using all available data. | The choice of groundwater irrigation has significantly positive effect on efficiency. | The model ignores any types of biases. |
| 2. | We conducted the Durbin-Wu-Hausman (DWH) test to determine whether groundwater choice is endogenous. | Farmers' groundwater irrigation choice decision is found to be endogenous. | Endogenous irrigation water source choice decision argues for addressing self-selection in productivity analysis. |
| 3. | Two separate SPF models are estimated using unmatched samples, one for groundwater irrigation and the other one is surface water irrigation. | TE score distribution is compared between the groups. | These models ignore any types of bias. |
| 4. | The PSM technique is used to make a counterfactual group for surface water irrigation using all samples. | A counterfactual group of groundwater users using 1:1 nearest neighbor matching procedure is constructed. | The PSM technique has addressed self-selection and overcomes observable biases. |
| 5. | After PSM, we checked the assumption of homogenous technology between the groups. | The test result confirms homogeneity between the groups. | The test result argues for separate estimation of SPF models for the two groups. |
| 6. | We also run a pooled model using matched samples with groundwater as a dummy variable. | We found a significant positive effect of the groundwater irrigation choice on rice yield. | Observable biases stemming from different sources are corrected. |
| 7. | Using matched samples, we run separate SPF models for surface and groundwater irrigated plots. | TE scores are estimated and compared for both groups. | Using matched samples addresses observable biases |
| 8. | The Average Treatment Effect on the Treated (ATET) is computed by comparing the yield difference between surface and groundwater irrigated plots using the matched samples. | The ATETs in different matching approaches are the average impact of treatment on those used in groundwater. | The ATETs control for selection biases. |

[1] 'Matching' refers to the process of pairing individuals in a treatment group with individuals in a comparison group based on their propensity scores.

farmers to form cooperatives for irrigation, while individual sellers dominate the groundwater irrigation market. Moreover, cooperatives are a good source of information about sustainable irrigation and conservative water use. Ultimately, farmers become aware about water usage and feel motivated for sustainable surface water irrigation. Ghazouani et al. (2012) argued that farmers' cooperatives can be more effective than the conventionally prescribed water user associations in irrigation and groundwater management. The positive coefficient with the variable extension service argues that extension service recipient farmers have higher probability to adopt groundwater irrigation. This is coherent with literature arguing importance of extension service in technology dissemination, but to some extent contradicts with the literature highlighting importance of extension service for up-scaling sustainable agriculture practices (please see Begho et al., 2022 for a recent review on related literature). Since environmental sustainability in extension policy comes after food security through enhancing productivity, an extension agent may prioritize groundwater over surface water since the former ensures higher yield.

The ownership and access of farmers to types of irrigation machinery is important to explain their choice of irrigation water source. Farmers who use diesel and manually operated irrigation machines have higher probability to utilize surface water, while their counterparts who use electricity operated irrigation machines are more likely to use groundwater. Since irrigation is a major cost component in Bangladesh, government provides subsidy on irrigation and the rate is comparatively higher for the electrically-powered irrigation machines (MoA and FAO, 2013). Hence cost as a barrier is more likely to motivate a diesel operated machine owner to explore the available surface water sources. Moreover, around 92% of the deep-tube wells which are used to extract groundwater are operated by electricity, while around 94% of the small-scale irrigation machineries, such as low-lift pumps mainly used for surface water irrigation, are operated by diesel (BADC, 2015). Manual irrigation system is used for surface water from nearby sources. Cost differences across irrigation machineries using different types of fuels is noted as an important factor defining farmers' irrigation decisions (Sharma and Sharma, 2006). Along with price and cost differences, literature also noted that transactional issues such as reliability, security and fast transfer can affect a farmer's irrigation decisions (Bjornlund, 2003). Since in all these aspects an owner will certainly have an upper hand, a farmer is more likely to extract groundwater, which is depicted by the positive sign with the dummy variable for the machine owner. In the Indian context, some literature argued that the irrigation machineries are mostly owned by the large farmers whereas the small and marginal farmers participate more in the water market to access water for irrigation (Sharma and Sharma, 2006).

The positive sign associated with the variable wage work argues that farmers participating in wage-earning activities are less likely to choose surface water as a source of irrigation over groundwater. This contradicts with Manjunatha et al. (2014), who observed farmers with significant income from non-crop activities, such as dairy, have less interest in farming and ultimately practice less intensive farming using surface water as the cost is relatively lower. Wage-earning activities are stressful, laborious, and uncertain, and less gainful. It is quite possible for a farmer to use earnings from wage-working activities to ease financial constraints of farming.

#### *3.3.3. Propensity score matching for finding the proper counterfactual group*

To develop a counterfactual group for the farmers using groundwater irrigation, we utilize the probit estimates and produce a propensity score (PS) for each plot based on the common support region. Afterward, we match each plot using surface water irrigation with a plot using groundwater irrigation with the closest PS. The density distribution of the PS for both surface and groundwater irrigated plots, both with and without a common support area, is presented in Fig. 3. Furthermore, to check the reliability of the matching quality of the data, we have conducted multiple tests to ensure that our data satisfies the balancing requirements of the PSM.

The Kernel density matching balancing test[2] shows that both surface water and groundwater irrigation adopters have identical characteristics after matching as opposed to the unmatched sample (Fig. 4). The standardized differences (% bias) for the mean values of almost all covariates between surface water and groundwater irrigation are less than 10%. This reconfirms that the balancing requirement is ensured, and there are significant overlaps in their propensity score distributions of the two groups.

**Table 3**
Distribution of plots by irrigation source.

| Irrigation source | % of plots | % of area |
|---|---|---|
| Surface water | 22.6 | 24.2 |
| Groundwater | 77.4 | 75.8 |

**Table 4**
Probit model estimate for factors determining groundwater irrigation adoption decision.

| Variables | Marginal effects |
|---|---|
| Age | -0.0004 (0.0003) |
| Education | 0.001 (0.001) |
| Farm size | -0.043 (0.006)*** |
| Family size | -0.019 (0.002)*** |
| Drought risk | 0.126 (0.009)*** |
| Machine owner | 0.062 (0.010)*** |
| Diesel | -0.139 (0.009)*** |
| Manual irrigation | -0.522 (0.026)*** |
| Agricultural cooperative membership | -0.049 (0.011)*** |
| Consumption and selling | 0.054 (0.009)*** |
| Wage work | 0.036 (0.010)*** |
| Extension service | 0.021 (0.012)* |
| Flood depth | -0.028 (0.001)*** |
| Southern | -0.092 (0.010)*** |
| Constant | 2.716 (0.125) |
| Log likelihood | - 2314.10 |
| LR chi$^2$ ($\chi^2$) | 2796.66*** |
| Pseudo $R^2$ | 0.3767 |

Note: *, **, *** indicate significance at 10%, 5%, 1% level, respectively. Figures in parentheses are standard errors.

### *3.4. SPF analysis to explain productivity and efficiency differences in rice production*

#### *3.4.1. Hypothesis testing and variance parameters for the SPF model*

The results of several hypothesis tests that were necessary to establish that the chosen model is suitable to explain the impact of irrigation water source choice on farming are presented in Table 5. We begin with the log-likelihood ratio (LR) test, which confirms that the selection of the translog functional form to be more suitable than the Cobb-Douglas one. Many past studies also claimed that the flexible translog production function is a better fit for describing the production system for both Bangladesh (e.g. Rahman, 2003; Alam et al., 2011) and global agriculture (e.g. Bravo-Ureta et al., 2020). Second, is the test of third-moment ($\mathrm{M3T} = \mathrm{m}_3/\sqrt{\frac{6\mathrm{m}_2^3}{\mathrm{N}}}$, where $\mathrm{m}_2$ and $\mathrm{m}_3$ are the 2nd and 3rd sample moments of the OLS residuals, respectively), which checks the null hypothesis that there is no skewness of the OLS residual (Schmidt and Lin, 1984). The estimated test statistic for both models is negative and confirms the rejection of the null hypothesis of the presence of

[2] The test is a statistical technique used in observational studies to assess the balance of covariates between treatment groups. This test is typically used to evaluate the effectiveness of propensity score matching, a commonly used method to control for confounding variables in observational studies.

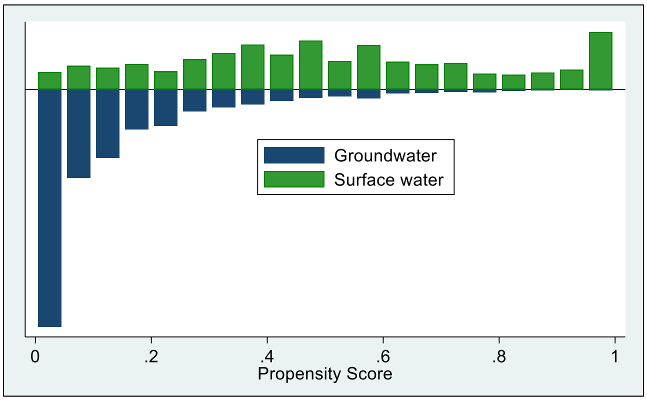


**Fig. 3.** Distribution of propensity score for groundwater and surface water irrigation. This score is generated by using Eq. 4, which includes several variables, namely: age, education, farm size, family size, drought risk, machine ownership, diesel usage, manual irrigation, membership in agricultural co-operatives, consumption and selling practices, wage work, extension service, flood depth, and a regional dummy variable for the Southern districts.

inefficiency effects. Rejection of the third hypothesis ($H_0 : \delta_1 = \delta_2 = ... = \delta_{15} = 0$) argues that the combined effects of factors involved in the technical inefficiency model are critical for understanding the production variations. Rejection of the fourth hypothesis ($H_0 : \delta_0 = \delta_1 = ... = \delta_{15} = 0$) argues in favor of incorporating the exogenous variables into the mean output function. The estimated coefficient of $\gamma$ is close to 1 and significantly different from zero (Table 6) confirming high level of inefficiency is present in the production process.

### 3.4.2. Explaining productivity differences in rice production

Table 6 presents the results of the SPF function for the matched sample. Labor, fertilizer and irrigation significantly enhance yield in the groundwater irrigated plots, while yield in a surface water irrigated plot increases significantly when farmers apply more fertilizer, irrigation and seed.

The estimated elasticity of labor, fertilizer and irrigation in the model for groundwater irrigation implies that a 1% increase in labor, fertilizer and irrigation will contribute to rice yield by 0.062%, 0.039%, and 0.059%, respectively. In surface water-irrigated plots, a 1% increase in fertilizer, irrigation and seed will increase rice yield by around 0.069%, 0.070% and 0.037%, respectively. The estimates of relatively smaller elasticities for all the input variables for both the groups are coherent with the literature arguing that in the context of land constrained countries like Bangladesh, land has a higher elasticity (almost close to unity) compared to other inputs (Rahman, 2003; Asadullah and Rahman, 2009; Selim, 2012).

The hybrid rice growers, irrespective of the choice of irrigation sources, obtained significantly higher yields than their counterparts cultivating HYV varieties. In the model for surface water irrigation, soil type dummy variables have a more dominant role in explaining yield differences than in the model for groundwater irrigation. In surface water-irrigated plots, yield is significantly higher in plots with loam soil than that of sandy-loam soil. In surface water-irrigated plots with sandy-loam soil, the yield is significantly lower compared to plots with clay soil but significantly higher than plots with sandy and clay-loam soil.

### 3.4.3. Determinants of inefficiency in the production process

Around 73% and 87% of the inefficiency explaining variables have significant effects in the models for surface water and groundwater, respectively. In both models, dummies for farm size, plot ownership, irrigation frequency, family size, drought risk and location of the plot have significant roles in explaining efficiency in rice production, though the direction of effects varies across the models. Additionally, variables such as age, extension service, and subsidy card play a significant role in the groundwater irrigation model, while education plays a significant role in the surface water irrigation model.

Farm size is important in explaining technical efficiency differences in rice production for both groups. Compared to farmers with smaller land holdings, the large farmers are more efficient in plots using groundwater, which is consistent with literature stating large farmers' capabilities to derive economies of scale and use agricultural innovations (Ram et al., 1999; Alam et al., 2011). In contrast, pioneered by the influential thoughts of Balogh and Schultz (1964), many authors observed small farmers are able to use available resources at the optimal level and attain higher productivity (Carter, 1984; Chand et al., 2011). All these may explain the negative correlation between farm area and efficiency in the model for surface water irrigation, where the landless, marginal, small and medium farmers attained higher efficiency level than the large farmers. The estimated higher efficiency for owned plots than rented plots is in line with earlier literature reporting relatively less fertile or low quality of land that landowners generally prefer to rent out to tenants (Rahman, 2003; Anik and Bauer, 2015).

In accordance with literature narrating the productivity and efficiency-improving role of education in Bangladesh (Asadullah and Rahman, 2009), we observe that the education variable has a positive coefficient in the model for surface water irrigation. Having a larger family positively influences the inefficiency of surface water irrigators, while the opposite is true for farmers using groundwater for irrigation. With increasing head of household age, we find farms gain efficiency in plots using groundwater, consistent with Wilson et al. (2001), who reported a positive correlation between experience and efficiency. Literature also reports older farmers' reluctance to change their years-old practices, while younger farmers are usually keen to explore beyond farming (Ainembabazi and Mugisha, 2014; Nyangena, 2008).

Subsidy card owners in groundwater irrigated plots operate with a higher level of efficiency than their counterparts who do not have subsidy cards. Our findings support Kumbhakar and Lien (2010), who argued that as subsidy reduces the utility of time, the farmer might spend more time in farming operations. However, the authors cautioned about drawing firm conclusions regarding this issue, as some researchers observed that this may also demotivate farmers to work efficiently (Karagiannis and Sarris, 2005). Additionally, subsidy may enable farmers to purchase inputs required for maximizing production or profit, by reducing their budget constraints.

Irrigation frequency is significantly and inversely associated with technical inefficiency of both surface water and groundwater irrigated plots. Farmers applying more numbers of irrigation are likely to maintain the water required at different stages of rice production. Along with increased yield and irrigation efficiency, literature reports many other benefits of irrigation rescheduling including reduced irrigation cost and the opportunity cost of water, and less chances of crop failure and run-off of chemical fertilizers (Adeniran et al., 2010).

Contradicting our general expectation, extension service is inversely correlated with efficiency in the model for groundwater irrigation, and is likely to be an outcome of inefficiency in the extension service, which is mentioned in several instances in the literature. However, it is important to mention the institutional constraints that conventional extension services face regarding the limited budget, manpower, and workload. However, one should carefully draw any firm conclusion regarding this issue.

The variable off-farm income has a negative sign in both models, implying that increasing off-farm income reduces inefficiency. Farmers, particularly those with limited land holdings, can use income from off-farm sources to compensate for their scale disadvantages (Fernandez-Cornejo et al., 2010). The role of off-farm income in overcoming credit constraints (Barrett et al., 2001) and enabling farmers purchasing productivity-enhancing inputs (Mishra et al., 2015), is well documented in the literature.

The positive sign associated with the dummy for the northern region indicates that both the surface water and groundwater irrigated plots

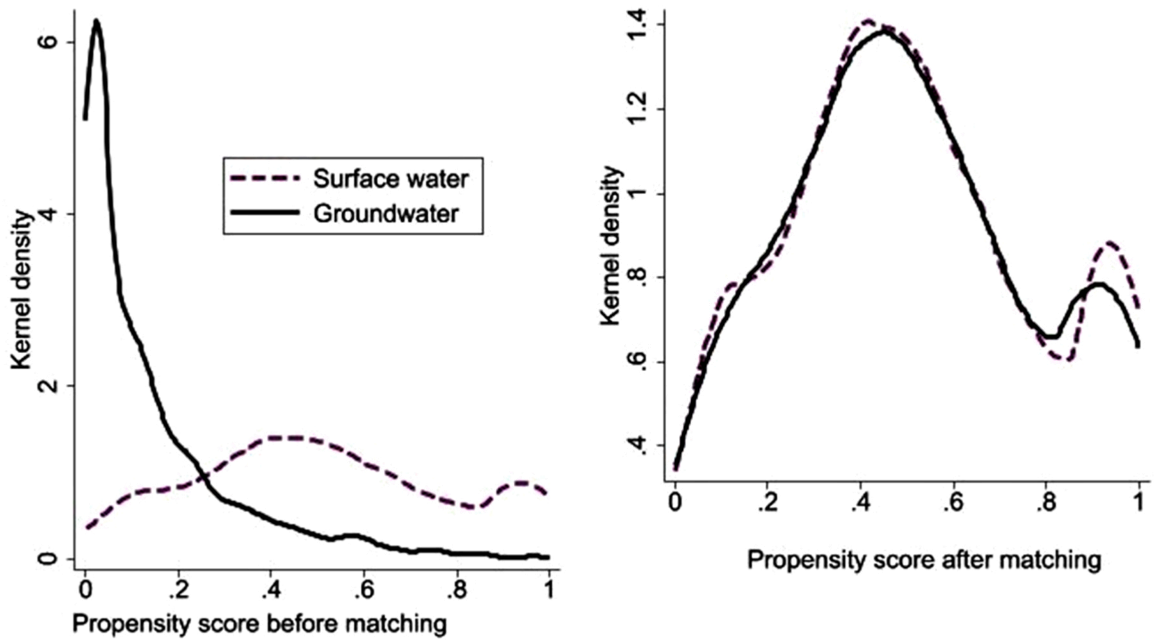


**Fig. 4.** Test of matching quality before and after propensity score matching.

**Table 5**
Hypothesis tests for model specification and statistical assumptions.

| Null hypothesis | Groundwater Test statistics | Groundwater Decision | Surface water Test statistics | Surface water Decision |
|---|---|---|---|---|
| Endogeneity test (DWH) | $\chi^2 = 2.71, df = 1, (p - value = 0.099)$ | | | |
| $H_0 : \beta_{jk} = 0$ | 38.94 | Reject $H_0$ | 52.88 | Reject $H_0$ |
| Third moment test (M3T) | − 51.319 | Reject $H_0$ | − 25.96 | Reject $H_0$ |
| $H_0 : \delta_1 = \delta_2 = ....\delta_{15} = 0$ | 234.84 | Reject $H_0$ | 88.84 | Reject $H_0$ |
| $H_0 : \delta_0 = \delta_1 = ....\delta_{15} = 0$ | 1040.10 | Reject $H_0$ | 792.86 | Reject $H_0$ |

Note: Critical value are taken from Table 1 of Kodde and Palm (1986) using 1% level of significance.

located in the southern region are more efficient than those in the northern region. Drought is prominent in the northern part of the country, which results in water and nutrient depletion in the soil (Prodhan et al., 2020). The declining trend in groundwater level, caused by groundwater irrigation and other purposes, is a major concern for farming in the north western region (Alauddin and Sharma, 2013; Dey et al., 2017; Rahman et al., 2021). For the same reason, plots in the drought-prone region are significantly less efficient in both models.

### 3.4.4. Technical efficiency in dry-winter season rice production by irrigation water sources

The descriptive statistics of the computed TE scores for the surface and groundwater irrigated rice plots are presented in Table 7. The mean efficiency scores for the surface and groundwater irrigated plots are 71.5% and 76.4%, respectively, and are equivalent to many past studies conducted with Bangladeshi rice growers (e.g. Rahman, 2003; Asadullah and Rahman, 2009; Selim, 2012).

The computed mean TE scores indicate that controlling technical inefficiency-related factors may increase yield by around 39.5% $[(100-71.5)/71.5]$and 30.9% $[(100-76.4)/76.4]$ in surface and groundwater irrigated plots, respectively. In accordance with earlier studies on rice farming in Bangladesh, the computed TE scores show a wide range of variation (Rahman, 2003; Rahman and Rahman, 2009). A relatively higher TE score and lower variation for the groundwater irrigated plots is not surprising since groundwater reduces risks and uncertainty related to the availability of water. Furthermore, the Kernel density of the estimated TE scores shows that the density of plots with higher TE is relatively higher among the groundwater irrigated plots (Fig. 3). Fig. 5.

### 3.4.5. Impact of irrigation water source on yield

The results of the estimated ATET presented in Table 8 support the existence of a significant difference between the yields of surface and groundwater-irrigated plots. All the signs of the ATETs in different matching approaches are positive and significant, indicating that yield in surface water-irrigated plots is significantly lower than those irrigated by groundwater.

## 4. Conclusions

The purpose of this study was to investigate productivity and efficiency of surface and groundwater-irrigated dry-winter rice-growing plots in Bangladesh. The SPF model was applied to the nationally representative BIHS 2018–19 dataset, which contains information from 6947 dry-winter rice-growing plots after correcting for heterogeneity arising from irrigation water-source choice decisions and biases arising from self-selection and observable factors.

Rice production is dominated by groundwater irrigation, accounting for three-fourths of irrigated plots and rice areas. Farmers experiencing drought risk are less likely to choose surface water for irrigation. Choice of surface water irrigation is positively associated with farm size, family size, plots with higher flood depth, membership in cooperative societies and users of diesel and manually operated irrigation machines. On the other hand, ownership of irrigation machines, working as wage labor and contact with extension services are positively associated with the likelihood of choosing groundwater. Farmers in the southern region are more likely to choose surface water for irrigation. Groundwater irrigated plots attained significantly higher yield and efficiency than surface water irrigated plots. Since yield and efficiency differences are lucrative incentives for farmers to adopt groundwater irrigation, there are implications for sustainability and the national budget. Moreover, several policy documents (e.g. National Water Policy, National Agricultural Policy, Integrated Minor Irrigation Policy, National Agriculture

**Table 6**
Parameter estimates of the stochastic production frontier model using matched sample.

| Variable | Groundwater | | Surface water | |
|---|---|---|---|---|
| Constant | 8.911 | (0.019)*** | 8.947 | (0.022)*** |
| Labor | 0.062 | (0.015)*** | 0.020 | (0.019) |
| Fertilizer | 0.039 | (0.013)*** | 0.069 | (0.017)*** |
| Irrigation | 0.059 | (0.014)*** | 0.070 | (0.015)*** |
| Seed | 0.019 | (0.016) | 0.037 | (0.019)* |
| Other inputs | 0.033 | (0.028) | 0.008 | (0.031) |
| Labor × Labor | 0.079 | (0.028)*** | -0.012 | (0.028) |
| Fertilizer × Fertilizer | -0.014 | (0.016) | -0.013 | (0.015) |
| Irrigation × Irrigation | 0.003 | (0.014) | 0.038 | (0.009)*** |
| Seed × Seed | -0.001 | (0.015) | 0.059 | (0.024)*** |
| Other inputs × Other inputs | 0.016 | (0.092) | 0.043 | (0.059) |
| Labor × Fertilizer | -0.031 | (0.032) | -0.107 | (0.034)*** |
| Labor × Irrigation | -0.100 | (0.033)*** | 0.012 | (0.022) |
| Labor × Seed cost | 0.088 | (0.033)*** | 0.009 | (0.035) |
| Labor × Other variable inputs | -0.041 | (0.077) | 0.035 | (0.063) |
| Fertilizer × Irrigation | -0.005 | (0.022) | -0.011 | (0.016)*** |
| Fertilizer × Seed cost | 0.089 | (0.030)*** | 0.002 | (0.025) |
| Fertilizer × Other variable cost | -0.042 | (0.059) | 0.072 | (0.044)* |
| Irrigation× Seed cost | -0.008 | (0.023) | -0.034 | (0.020)* |
| Irrigation× Other variable cost | 0.011 | (0.056) | -0.075 | (0.035)** |
| Seed cost × Other variable cost | -0.096 | (0.064) | -0.114 | (0.060)** |
| Hybrid | 0.130 | (0.015)*** | 0.153 | (0.014)*** |
| Clay | 0.008 | (0.029) | 0.068 | (0.037)* |
| Loam | 0.034 | (0.019)* | 0.011 | (0.022) |
| Sandy | -0.015 | (0.032) | -0.086 | (0.036)** |
| Clay loam | -0.003 | (0.016) | -0.040 | (0.019)** |
| **Technical inefficiency model** | | | | |
| Landless farm | 0.951 | (0.249)*** | -0.738 | (0.272)*** |
| Marginal farm | 1.139 | (0.231)*** | -0.355 | (0.216)* |
| Small farm | 1.216 | (0.208)*** | -0.565 | (0.204)*** |
| Medium farm | 1.668 | (0.202)*** | -0.564 | (0.198)*** |
| Age | -0.011 | (0.003)*** | -0.004 | (0.003) |
| Education | 0.003 | (0.011) | -0.027 | (0.011)** |
| Family size | -0.051 | (0.015)*** | 0.066 | (0.015)*** |
| Subsidy card | -0.721 | (0.109)*** | -0.142 | (0.094) |
| Land parcel | 0.010 | (0.009) | -0.005 | (0.009) |
| Irrigation frequency | -0.023 | (0.003)*** | -0.007 | (0.003)** |
| Extension service | 0.276 | (0.143)* | -0.184 | (0.140) |
| Own plot | -0.162 | (0.094)* | -0.228 | (0.092)** |
| Off-farm income | -0.275 | (0.097)** | -0.466 | (0.093)*** |
| Drought risk | 0.483 | (0.111)*** | 0.265 | (0.116)** |
| Northern | 0.368 | (0.095)*** | 0.160 | (0.089)* |
| Constant | -1.561 | (0.033)*** | -0.524 | (0.310)* |
| **Variance and other model statistics** | | | | |
| Gamma ratio ($\gamma$) | 0.969*** | | 0.981*** | |
| Log-likelihood | 81.32 | | -273.68 | |

Note: ***, **, and * indicate significant at 1%, 5%, 10% level, respectively. Figures in parentheses are standard errors. Prior to estimation, all the input variables $(X_1, X_2, \ldots, X_5)$ were mean corrected and therefore, the coefficients of these variables can be described as output elasticities of the corresponding inputs evaluated by their mean.

Extension Policy, National Water Management Plan: Development Strategy, and Bangladesh Water Act) emphasize increasing surface water irrigation coverage, which seems difficult to achieve given these results.

Our results reveal the presence of significant inefficiency in the rice production system of Bangladesh. The estimated SPF models show robust effects of irrigation, seed and its quality, fertilizer, and soil type on rice production. The major factors explaining inefficiency are farm size, land ownership, irrigation frequency, off-farm income, education, extension, and subsidy.

Several policy options can be proposed from this research. However, these are not straightforward as there is a dilemma between enhancing rice productivity and efficiency, achieved mainly through groundwater irrigation, while tackling the falling water table in many areas of Bangladesh. First, since dry-winter rice farming requires substantial supplementary irrigation primarily from groundwater, policymakers must devise innovative strategies to encourage surface water irrigation, which is less productive and efficient at present. Rebalancing subsidies toward surface water irrigation may be an effective strategy since we observed a negative correlation between subsidy and efficiency. Second, information on surface water irrigation should be provided to the farmers through cooperatives and extension services, while acknowledging the efficiency-reducing role of extension, which in turn requires redressing the existing extension system in the country. Third, farmers in the drought-prone northern region require special attention since they operate at a lower efficiency level irrespective of the irrigation water source. Fourth, lower efficiency in rented-in plots would require long-term rental arrangements so that farmers have incentives to invest in efficiency-enhancement measures. The security of tenure will incentivize farmers to adopt yield enhancing measures, e.g., better soil fertility management options, other production enhancing inputs, etc.

We did not outright provide support for further investment in groundwater irrigation infrastructure, although the evidence presented a robust positive effect of groundwater irrigation on rice yield and efficiency. This is mainly due to the sustainability concern regarding the falling groundwater table, resulting from the high level of groundwater extraction for agriculture and other domestic and industrial uses. We realize that it is unconventional not to suggest policies that were dominant in the results, i.e., to vigorously promote groundwater irrigation sources further. However, if we address the other structural causes identified in the results outlined above, Bangladesh may be able to tip the balance of irrigation for rice production from groundwater to surface water sources without sacrificing production.

The present study is based on a nationally representative plot-level cross-sectional data, which can provide in-depth information about

**Table 7**
Technical efficiency in dry winter season rice production by irrigation sources.

| Efficiency levels | Proportion of rice plots | |
|---|---|---|
| | Groundwater | Surface water |
| Up to 70% | 32.99 | 42.68 |
| 71–80% | 20.57 | 21.27 |
| 81–90% | 29.24 | 24.84 |
| 91% and above | 17.20 | 11.21 |
| Efficiency scores | | |
| Mean | 0.764 | 0.715 |
| SD | 0.151 | 0.166 |
| Minimum | 0.184 | 0.152 |
| Maximum | 0.979 | 0.960 |

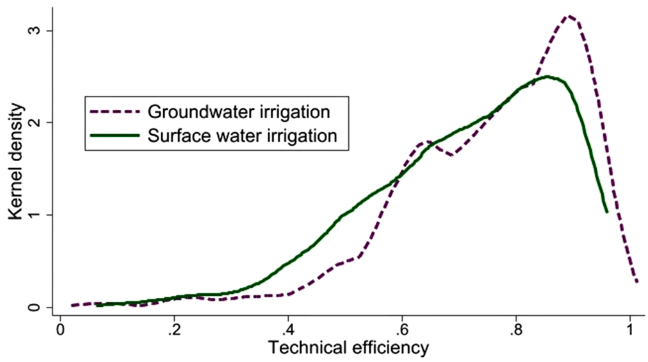


**Fig. 5.** Distribution of technical efficiency index for groundwater and surface water irrigation. This technical efficiency index is estimated by using inefficiency effects variables such as age, education, family size, irrigation frequency, land parcel, off-farm income, and dummy variables for farm size categories, extension service, land ownership, subsidy card, and Northern region.

**Table 8**
The average treatment effect on the treated of groundwater irrigation on rice yield.

| | Propensity score matching | Nearest-neighbour matching | Regression adjustment | Inverse probability weight |
|---|---|---|---|---|
| Groundwater versus surface water | 316.50 (76.99)*** | 285.33 (75.73)*** | 325.66 (55.63)*** | 330.93 (45.32)*** |

Note: *** indicate differences are significant at the 1% level, and parentheses values are the robust standard errors.

the existing scenario at a point in time. Farmers' choices of irrigation sources may change over time based on changes in socioeconomic conditions and/or knowledge of declining water-table levels. This will require using panel data from similar nationally representative surveys to track such changes.

Results obtained from this study and policy implications drawn thereof can be generalized for other regions depicting similar rice production and farming practices, socio-economic circumstances of farmers, incidences of falling water tables, overexploitation of groundwater as well as declining availability of surface water for irrigation. This is because we have used a quantitative approach to a large set of nationally representative plot-level data, which provided insight into the underlying structural relationships of the regressors used in the econometric model, which was largely independent of the study location and/or data collection period. Therefore, we are confident that our results and derived policy implications have wider appeal for policy-makers and relevant stakeholders concerned with options and/or mechanisms to address similar challenges in other regions and areas beyond our study location.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

Data will be made available on request.

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