Chapter 8: Measurement and sources of technical efficiency of on-farm water use in the Sudan's Gezira scheme

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8.1 Introduction

The literature identifies two common approaches for estimating technical efficiency. One approach is based on non-parametric, non-stochastic, linear programming. This suffers from the criticism that it does not take into account the possible influence of measurement error and other noise in the data (Coelli, 1995). The second approach uses econometrics to estimate a stochastic frontier function, and to estimate the inefficiency component of the error term. The disadvantage of this approach is that it imposes an explicit and possibly restrictive functional form on the technology. However, this approach is chosen here because it permits estimation of the determinants of the inefficiency of the producing unit, which is the focus of this study.

Farrell (1957) suggested a deterministic method of measuring the technical efficiency of a firm in an industry by estimating a frontier production function. Several extensions of Farrell's model have been made. The most recent have been the stochastic frontier models developed by Meeusen and van den Broeck (1977). Stochastic frontier models were also used extensively (Coelli, 1995).

The stochastic frontier model assumes an error term with two additive components – an asymmetric component, which accounts for pure random factors (υi) and a one-sided component, which captures the effects of inefficiency relative to the stochastic frontier (u_i).The random factor (υ) is independently and identically distributed with N (0, υ) while the technical inefficiency effect, (u) is often assumed to have a half normal distribution |N (0, υ)|. The model is expressed as:

$$Y_i = x_i \beta + (\upsilon_i - u_i) \qquad (1)$$

$$TE_i = z_i \delta$$

Where xi is the vector of input quantities of the ith firm and z is the vector of firm-specific factors determining the inefficiency. The β and δ are unknown parameters to be estimated together with the variance parameters expressed as $\sigma^2 = \sigma_\upsilon^2 + \sigma_u^2$ and $\gamma = \sigma_u^2/(\sigma_v^2 + \sigma_u^2)$. The parameter, x, has a value between zero and one such that the value of zero is associated with the traditional response function, for which the non-negative random variable, u_i, is absent from the model.

Technical efficiency is defined as $TE_i = \exp(-u_i)$. It is predicted using the conditional expectation of $TE_i = \exp(-ui)$, given the composed error term in equation (1). In this specification, the parameters, β, σ, σu, and γi can be estimated by the maximum likelihood method, using the computer program, FRONTIER Version 4.1 (Coelli, 1996). This computer program also computes estimates of efficiency.

8.2 Methodology

To assess the efficiency of on-farm water use, a fixed allocatable input model was used to estimate each model's parameters using the ordinary least squares procedure. Data used in this study are obtained from a survey in the Abdelhakam and El Medina blocks of the central group of the Gezira scheme conducted in 2007. The study area is one of the most productive areas of the Gezira scheme.

The cross-sectional data for the sample of 193 household is used to estimate a Cobb-Douglas stochastic production frontier 4. A single equation model is justified since input allocations and outputs are observed, implying the general input allocation case where technological relationships can be estimated directly without explicit assumptions that restrict either behavior or technology (Just et al., 1983). (See Chapter 7 for a description of the sampling method.)

A stochastic frontier production function was used to examine the economic efficiency and the determinants of inefficiency in the use of irrigation water in the Gezira scheme. The WP production function for the selected crops consists of the dependant variable – WP – and two sets of variables that represent the technical efficiency variables and others responsible for inefficiencies. The technical efficiency variables include quantitative variables, such as the cultivated area in feddan; product price in SDG/kg, labor used in man-days/feddan, and the cost of inputs, such as water, fertilizers, and seed in SDG/feddan. (SDG – Sudanese pound.) The inefficiency variables include qualitative factors that affect water management, such as land tenure (owned, rented, or shared), and the location of the farm from the distribution points (head, middle, tail). Also included as inefficiency variables were the farmers' perceptions, such as their participation in farmers' field schools (FFS), participation in WUAs, their awareness of the right time to irrigate crops, their awareness of when to stop irrigation, their perceptions on crop water requirements, water availability to the farm in relation to crop requirements, similarity of water at the head and tail of the canal, effective membership in WUAs, participation in field days, method of determining the quantity of water demanded, and the quantitative variable, the total number of irrigations. It is worth noting that some of the qualitative variables have more than one dummy variable. The number of dummy variables depends on the number of factors attributed to the variable in question. These variables were subjected to many iterations of the frontier production model to select the most appropriate factors responsible for technical efficiency and the sources of inefficiency. Variables in the frontier production function are as follows:

Y is the water productivity (output/quantity of water applied)

Efficiency variables

X_1 is the product price (SDG/kg)

X_2 is the water cost (SDG/feddan)

X_3 is the fertilizer cost (SDG/feddan)

X_4 is the amount of labor used (man-days/feddan)

X_5 is the seed cost (SDG/feddan)

Inefficiency variables

X_6 is the participation in FFS (participate = 1, otherwise = 0)

X_7 is the participation in WUA (participate = 1, otherwise = 0)

X_8 island tenure (owned = 1, otherwise = 0)

X_9 is awareness about the right time of irrigating the crop (aware = 1, otherwise = 0)

X_{10} is awareness about when to stop irrigation (when the water covers two-thirds of the ridge = 1, otherwise = 0)

X_{11} is the farmer perception on crop water requirement (as required = 1, otherwise = 0)

X_{12} is the location of the farm (head = 1, otherwise = 0)

X_{13} is the degree of similarity of water at the head and tail of the canal (similar = 1, otherwise = 0)

X_{14} is membership in a WUA (member = 1, otherwise = 0)

X_{15} is participation in field days (participated = 1, otherwise = 0)

X_{16} is farmer perception of the contribution of the WUA to efficient use of irrigation water (apparent contribution = 1, has no contribution = 0)

X_{17} is the determination of the demanded quantity of water (the farmer = 1, the selected farmer or field inspector = 0)

X_{18} is the total number of irrigations

8.3 Results and discussion

As mentioned before, a stochastic frontier production function was used to examine the economic efficiency and identify the determinants of inefficiency in the use of irrigation water in the Gezira scheme. The WP production function for the selected crops consists of the dependant variable, the WP, and two sets of independent variables that represent the technical efficiency variables and the variables responsible for inefficiencies. When the amount of water required for the crops was compared with the actual amount used, it was found that there was over-irrigation for all crops in the study area. For the summer crops, farm water use efficiency (FWUE) for sorghum ranged between 0.516 and 0.997, with an average of 0.83, while for groundnut it ranged between 0.498 and 0.99, with an average of 0.83. For the winter wheat crop, FWUE ranged between 0.86 and 0.988, with an average of 0.96. These estimates indicate that farmers over-irrigated sorghum and groundnut by 17% and wheat by 4% (Table 8.1). Therefore, when rationalizing the use of scarce water for the summer crops, it is possible to save an enormous amount, which can be used to expand the sorghum and groundnut growing areas, and thus increase total production. Alternatively other crops could be produced. The farmers can increase crop yields considerably under current levels of water use and with improved water and crop management practices. Either option can contribute significantly to food security in Sudan. The estimates of FWUE for sorghum and groundnut indicate a wide technological gap between the required practices and actual water application. Therefore, improving the water use efficiency for these crops can contribute greatly to overall water use efficiency in the study area and offers a high potential for saving water. These results are consistent with the findings of a recent FAO study, which concluded that water productivity seems to be lowest in water scarce regions of agriculturally based economies (FAO, 2002).

Table 8.1. Farm water use efficiency for the main food crops in the Gezira scheme.

Crop	Minimum	Maximum	Average
Sorghum	0.516	0.997	0.83
Groundnut	0.498	0.99	0.83
Wheat	0.86	0.99	0.96

The maximum likelihood estimates for the parameters in the stochastic frontier model are presented in Tables 8.2, 8.3, and 8.4. In respect of product prices, the results indicated that wheat and groundnut prices have significant positive effects on WP. This means that the prices of these crops respond positively to WP. This is normal because an increase in the product price will be expected to result in an increase in yield and consequently an increase in the WP. In this case, water consumption might be increased and that may cause an increase in the price of irrigation water which then reduce water consumption again.

Since water prices in the study area were highly subsidized, they did not have a major quantitative impact on water allocations. Previous studies showed that water demand is inelastic at low price changes (Ahmed, 2002). Because water prices are very low in Sudan, only high increases in water charges can reduce the amount of water used for irrigation, which in turn will greatly reduce the farmers' income. As expected, water costs for sorghum, groundnut, and wheat have statistically positive coefficients of about 0.08, 0.12, and 0.34, respectively. The estimates of

Table 8.2. Maximum likelihood estimates of the Cobb-Douglas stochastic production frontier function for sorghum.

Variable	Coefficient	Estimate	t-ratio
Intercept	β_0	7.60	16.8
Price of sorghum (SDG/kg)	β_1	-4.53	1.4
Water cost (SDG/feddan)	β_2	0.08	3.9
Fertilizer cost (SDG/feddan)	β_3	-0.01	27.3
Labor used (man-days/feddan)	β_4	0.03	1.5
Seed cost (SDG/feddan)	β_5	-0.003	24.1
Intercept	δ_0	1.65	22.4
Participation in FFS	δ_1	-0.016	44.0
Participation in WUA	δ_2	-0.008	22.1
Awareness about the right time of irrigating the crop	δ_3	0.068	1.2
Awareness about when to stop irrigation	δ_4	0.063	1.2
Awareness about when to stop irrigation	δ_5	0.059	1.7
Farmer perception on crop water requirement	δ_6	-0.041	1.1
Who determine the demanded quantity of water	δ_7	0.064	1.6
Total number of irrigations	δ_8	-0.992	18.5
Sigma-squared		0.006	2.6
Gamma		90.8	152.0

the individual coefficients of the water constraint suggest that an increase in water availability is allocated most heavily to crops with relatively higher requirements, like groundnut, rather than to crops with relatively low water requirements, such as sorghum. For this reason, sorghum responds to increased water costs better than groundnut. In this regard, improvements in water management have the potential to optimize water use at the farm level. Thus, sound extension strategies will be needed to increase the farmers' awareness to optimize water use at the farm level. This, in turn, will reduce the adverse effects of salinization and water logging – problems which are caused by over-irrigation – on the productivity of the land. Thus, by achieving optimal water use, it is possible to increase crop productivity in the study area, while, at the same time, ensuring the sustainable use of resources, both water and land.

The elasticity of the farm size is estimated at -0.002 for wheat, indicating that expansion in this winter crop will negatively affect the available amount of water. For groundnut, the situation may be slightly different because the crop is considered a summer crop, which receives appreciable amounts of water during the rainy season. It is worth noting that the farm size reduces inefficiency, as indicated by the positive and significant coefficient for cultivated land (0.032). This may be due to the low level of resources and technology that allow efficient operation. While the coefficient for crop establishment labor is statistically significant, the coefficients for fertilizer and seed costs for sorghum are negative, but significantly different from zero, with coefficients of -0.0079 and -0.032. This unexpected result may be associated with the water regime.

For the inefficiency variables, participation in FFS, participation in WUA, farmers'

Table 8.3. Maximum likelihood estimates of the Cobb-Douglas stochastic production frontier function for groundnut.

Variable	Coefficient	Estimate	t-ratio
Intercept	β_0	6.070	7.40
Price of groundnut (SDG/kg)	β_1	0.580	1.14
Water cost (SDG/feddan)	β_2	0.115	1.88
Area of groundnut area (feddan)	β_3	0.032	1.62
Seed cost (SDG/feddan)	β_4	0.018	25.0
Labor used (man-days/feddan)	β_5	0.063	86.1
Intercept	δ_0	-1.00	-63.8
Participation in FFS	δ_1	0.078	82.4
Participation in WUA	δ_2	0.312	2.19
Land tenure	δ_3	-1.290	90.3
Awareness about the right time of irrigating the crop	δ_4	-0.122	91.7
Awareness about when to stop irrigation	δ_5	-0.056	56.9
Farmer perception on crop water requirement	δ_6	-0.125	1.19
Location of the farm	δ_7	-0.335	-2.13
Similarity of water at the head and tail of the canal	δ_8	-0.011	-0.098
Membership in WUA	δ_9	-0.251	2.09
Participation in field days	δ_0	-0.137	-1.28
Farmer perception on the contribution of WUA to efficient use of irrigation water	δ_{11}	-0.158	-1.49
Who determine the demanded quantity of water	δ_{12}	-0.211	-1.79
Total number of irrigations	δ_{13}	-0.294	-95.6
Sigma- squared		0.069	24.9
Gamma		98.6	107.0

perceptions of crop water requirements, and the total number of irrigations are the main sources of technical inefficiency for the sorghum crop with coefficients of -0.016, -0.008, -0.041, and -0.99, respectively. Thus, a policy to increase farmers' awareness is expected to reduce the inefficiencies associated with increasing farmers' awareness of irrigation management. For groundnut, the results indicated that the proximity of the farm to the water point or minor canal, farmer's supervision to manage water distribution, and the total number of irrigations are the main sources of inefficiency with coefficients of -0.34, -0.21, and -0.29. In addition to these variables, the farmers' awareness of the right time for irrigation, when to stop irrigation, and the farmers' perceptions of crop water requirements, and effective membership in the WUA are the main sources of inefficiency with coefficients of -0.12, -0.056, -0.12, and -0.25, respectively.

Some researchers argue that tenancy management, such as share-cropping, results in an inefficient allocation of resources as well as reduced incentives to improve agricultural lands (Ahmed, 2002). The coefficients for the land contract (cultivating own land) is statistically significant and different from zero. This indicates that

Table 8.4. Maximum likelihood estimates of the Cobb-Douglas stochastic production frontier function for wheat.

Variable	Coefficient	Estimate	t-ratio
Intercept	β_0	6.13	6.31
Wheat area (feddan)	β_1	-0.002	-0.15
Labor used (man-days/feddan)	β_2	0.059	0.87
Water cost (SDG/feddan)	β_3	0.335	1.59
Wheat price (SDG/kg)	β_4	0.780	1.90
Intercept	δ_0	0.004	1.45
Participation in FFS	δ_1	0.015	0.33
Participation in WUA	δ_2	0.023	0.61
Land tenure	δ_3	-0.125	0.65
Awareness about the right time of irrigating the crop	δ_4	-0.030	-0.58
Awareness about when to stop irrigation	δ_5	0.028	0.44
Awareness about when to stop irrigation	δ_6	-0.123	-1.30
Farmer perception on crop water requirement	δ_7	0.028	0.39
Farmer perception on crop water requirement	δ_8	-0.340	-0.58
Description of water available to the farm in relation to crop requirement	δ_9	-0.029	-0.39
Location of the farm	δ_{10}	0.029	0.36
Location of the farm	δ_{11}	-0.109	-1.02
Similarity of water at the head and tail of the canal	δ_{12}	-0.028	-0.37
Membership in WUA	δ_{13}	-0.037	-0.72
Participation in field days	δ14	0.042	0.07
Who determine the demanded quantity of water	δ_{15}	0.006	0.12
The total number of irrigations	δ_{16}	-0.280	-1.24
Sigma-squared		0.009	5.54
Gamma		0.622	6.79

the levels of inefficiency associated with share-cropping and the different levels of inefficiency associated with the land tenure system can be explained by the restrictions involved and the interaction between labor and the input markets. It is worth noting that share-cropping involves a commitment by both partners to share the costs of inputs and the benefits of outputs, but places considerable restrictions on the rights of the share-cropper. Moreover, the share-cropper is responsible for providing the labor input to perform the field operations and, thus, is responsible for any sub-optimal use of labor. Therefore, despite the contribution of the landowner, in terms of inputs, lack of autonomy on the part of the share-cropper in this partnership explains the inefficiency of share-cropping. The econometric result indicates that land transactions, such as share-cropping, that involved restrictions on the farmers' decision-making are technically inefficient compared to owner-cultivated tenure. Finally, farmers who are trained are more efficient than those who received no training in improving the technical inefficiency of their farming. This result is consistent with the theory of adoption of innovation, as training and increased awareness on the farmer's part enhance technology uptake and perhaps the returns associated with the adoption.

One can conclude that product price, water prices, farm size, labor used, and inputs used are the major factors that have significant influence on the technical efficiency of irrigation water. Farmers' awareness of optimal water use at the farm level, participation in FFSs, effective participation in a WUA, location of the farm, and the land tenure system (cultivating one's own land) are the main factors that have significant influence on technical inefficiency for the cultivated crops in the Gezira scheme. Thus, a policy to increase farmers' awareness is expected to reduce the inefficiencies associated with the irrigation management. The study concluded that policies create most of the conditions that determine the levels of water use efficiency, such as farm size, water allocation and costs, cropping patterns, input subsidies, and crop prices. In this respect, policy setting is really needed in the crop areas and crop-mix, given an increasing trend towards free market prices that create conflicts in resource use between the national and farm levels resulting from conflicting objectives. The study recommends conducting research programs to develop varieties with low consumptive water use coupled with agronomic recommendations that increase crop productivity and conserve soil and water resources. A variety of research areas will need to be considered in the light of the policy and institutional constraints. These include the monitoring of economically optimum crop water requirements that maximize returns on irrigation water under changing conditions of commodity prices and adoption of free-market policies, efficient water pricing systems, institutional aspects of water distribution among users, and regulations regarding irrigation water use.

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