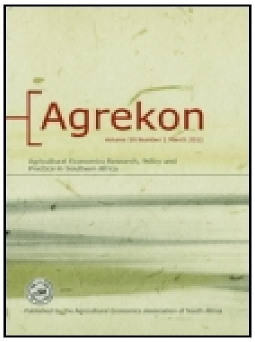

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SIMULATION OF EFFICIENCY IMPACT OF DRAINAGE WATER RE-USE: CASE OF SMALL-SCALE VEGETABLE GROWERS IN NORTH WEST PROVINCE, SOUTH AFRICA

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ABSTRACT

This paper focuses on estimating the effect of drainage water reuse on the technical efficiency of small-scale vegetable growers in South Africa applying a data envelopment analysis (DEA). In the semi-arid North West Province of South Africa water scarcity and the soon to be implemented water charges have urged farmers in small-scale irrigation schemes to evaluate the efficiency of their water use. Data on 60 farmers were used to estimate the level of technical efficiency and the effect that drainage water re-use could have on efficiency levels. This effect of water reuse was simulated by a 5, 10, 15 and 20 per cent reduction in water use at farm level. A Malmquist productivity index was calculated to evaluate the effect of these reductions. The main finding was that under current farming conditions many farmers operated at sub-optimal levels of technical efficiency. While a reduction in water use evidently increased factor productivity for most farms, the effect clearly varied strongly between farms. This confirms the need to take a systems approach for this type of evaluations.

Keywords: data envelopment analysis, small-scale irrigation, South Africa, water reuse, simulation

1 INTRODUCTION

With growing demands for freshwater resources in water-scarce countries, pressure on the agricultural sector to give up part of its allocation to prime-use sectors such as households and industries has increased. Meanwhile, agriculture has to continue producing food and fibre to satisfy current and future demand to guarantee food security (World Bank, 2005). Under such conditions, reuse of water in irrigation could become important for supplementing supply and increasing the efficiency of water use (Minhas *et al.*, 2006; World Bank, 2005; Abdel Khalek *et al.*, 2003; Choukr-Allah and Hamdy, 2003).

The increasing pressure on available water resources prompts the irrigation sector to find ways to improve its performance (Malano *et al.*, 2004). This is also the case for South Africa. The National Water Resources Strategy, as a part of the National Water Act (Act 36 of 1998), was designed to address the lack of

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efficiency in water use (Grové, 2006). Specifically for the small-scale irrigators, the approaching introduction of water charges gives rise to extra concerns regarding more efficient water use. Grové (2006) and Grové *et al*. (2006) introduce deficit irrigation as one of the possibilities for optimising water use. However, deficit irrigation may impact on the production schedule and increase yield variability. Adoption among risk-averse farmers may therefore be limited (Grové, 2006). Alternatively, water reuse schemes could be considered as they also show great potential for saving valuable freshwater resources (World Bank, 2005; Tanji & Kielen, 2002; Guerra *et al.*, 1998).

The aim of this paper is to study the effect that water reuse could have on the production efficiency of individual smallholders in the North West Province of South Africa. Since irrigated agriculture is a multiple input-multiple output process, it is not an easy task to ascertain how efficient the use of inputs is. Considering water in an isolated manner through simple measures such as "output per m^3" neglects differences among farms in non-water input use and may therefore lead to wrong conclusions (Malana & Malano, 2006; Rodríguez Díaz *et al*., 2004; Coelli *et al*., 2002). This motivates the need for a systems approach in studying the impact of water reuse on farmers' efficiency. Hence, in this study data envelopment analysis (DEA) is used to yield consistent measures of efficiency.

First the current efficiency levels of the farmers are calculated. To this end detailed survey data collected in 2005 from 60 sampled farmers spread over 13 small-scale irrigation schemes in the Zeerust Municipality were used. In the second step of the analysis, a number of scenarios were developed to account for different levels of water saving at scheme level that can be achieved by drainage water reuse. A Malmquist productivity index is used to compare the current efficiency measures with the efficiency levels under the water reuse scenarios. In this way the potential impact of the introduction of a water reuse scheme is evaluated.

In the literature, several studies are found that use DEA methodology to study the efficiency of agricultural production in developing countries (Haji, 2006; Malana & Malano, 2006; Chavas *et al*., 2005; Binam *et al*., 2004; Dhungana *et al*., 2004; Coelli *et al*., 2002). However, none of them specifically focused on the reuse of water. On the other hand, various studies discussed reuse of drainage water (e.g., Corwin *et al.*, 2008; Qadir *et al.* 2007; Minhas *et al.*, 2006; Tanji & Kielen, 2002; Willardson *et al*., 1997), but most of these are technical papers discussing mainly the constraints linked to the composition of the irrigation water or the effects of the reuse on crop growth and water and salt balances. If efficiency impacts are mentioned, they consist only of one-dimensional measures like crop yield per unit of water or net benefit per unit of water (Guillet, 2006). The novelty of this paper is that it introduces a systems measure of efficiency in the evaluation of drainage water reuse schemes at the farm level. This focus is highly relevant given the growing water scarcity and the increasing interest in water re-use.

2 POTENTIAL OF DRAINAGE WATER REUSE

Efficient reuse of drainage water may help minimise the demand–supply gap, thus increasing production or saving water (Minhas *et al.*, 2006). It is now widely accepted that water reuse at different system levels impacts positively on the efficiency. However, the use of drainage water at the scheme level is determined and limited by soil type, crops to be grown, agroclimatic conditions and the composition of drainage water (Minhas *et al.*, 2006; Tanji & Kielen, 2002). It is important to recognise that drainage water is normally of inferior quality compared to original irrigation water. Therefore, when reusing drainage water adequate attention needs to be paid to management measures to minimise short- and long-term harmful effects on crop production, soil productivity and water quality at project or basin scale (Abdel Khalek *et al.*, 2003; Tanji & Kielen, 2002).

Different schedules for drainage water use can be identified: firstly, drainage water of sufficiently good quality can be used directly for crop production; secondly, drainage water can be reused in combination with freshwater resources. This type of use involves blending drainage water with freshwater or using both water sources cyclically. A further distinction can be made between intra-seasonal cyclic use (the two water sources are alternated in the cropping season) and inter-seasonal cyclic use (the two water resources are used separately over the seasons for different crops) (Oster & Grattan, 2002; Tanji & Kielen, 2002). It is mainly the blending with freshwater or the cyclical use within a cropping season that has the potential to reduce freshwater demand.

3 METHODOLOGY

3.1 Measuring efficiency

The efficiency concept used in this study refers to the global relationship between outputs and inputs, with production as the interaction of the different factors involved (Rodríguez Díaz *et al.*, 2004). The concept originates from the seminal work on technical efficiency by Farrell (1957). Technical efficiency is defined as the ability of a farm to produce the maximum feasible output from a given bundle of inputs or to use minimum feasible amounts of inputs to produce a given level of output. These two definitions of technical efficiency lead to the output-oriented and the input-oriented efficiency measure respectively (Dhungana *et al.,* 2004; Rodríguez Diaz *et al.*, 2004; Coelli *et al.*, 2002). In this study the input-oriented model is used, because water is considered as a limiting input with the objective of saving freshwater and not per se to find ways of how to increase production.

The methodology used for measuring the efficiencies in this study is DEA. This type of analysis provides a straightforward approach for calculating the efficiency gap between the actions of individual producers and best practice, inferred from observations on the inputs used and the outputs generated by efficient farms. The method was introduced by Charnes *et al*. (1978). It is a deterministic, non-parametric approach, which applies mathematical programming to obtain efficiency values. Characteristic of DEA is that a piecewise frontier surface is assembled by solving a sequence of linear programming problems (see Eq. 1), one for each farm, simultaneously relating each farm to the constructed frontier. By using actual observations, the frontier created envelops the observed input and output data of all farms.

The model is presented here for a case where there are data on K inputs and M outputs for each of the N farms. For the i^{th} farm, input and output data are represented by the column vectors x_i and y_i respectively. The K by N input matrix *X*, and the M by N output matrix *Y*, represent the data for all N farms in the sample.

The DEA model to calculate the technical efficiency is in this case (equation 1):

$$Min_{\theta\lambda}\theta ,$$

$$\text{subject to} \quad -y_i + Y\lambda \geq 0; \quad \theta x_i - X\lambda \geq 0, \quad N1'\lambda = 1, \quad \lambda \geq 0 \qquad (1)$$

where θ is a scalar, *N1* is an N by 1 vector of ones, and λ is an N by 1 vector of constants. Using the variables λ and θ, the model is solved once for each farm, searching for the largest radial contraction of the input vector x_i within the technology set. The value of θ corresponding with this contraction is the technical efficiency score for the i^{th} farm. This score will always be between zero and one; one indicating that the farm lies on the frontier and is efficient. The first constraint ensures that output produced by the i-th farm is smaller or equal to that on the frontier. The second constraint limits the proportional decrease in input use, when θ is minimised, to the input use achieved with the best observed technology. Constraint three is a convexity constraint that creates a variable returns to scale (VRS) specification of the model. Without that convexity constraint, Eq. (1) gives the constant returns to scale (CRS) specification. Under the CRS specification it is assumed that farms are operating at their optimal scale (Fraser & Cordina, 1999). In the case of agriculture, it is assumed that increased amounts of inputs do not proportionally increase the amount of outputs. For instance, when the amount of water to crops is increased, a linearly proportional increase in crop volume is not necessarily obtained. For this reason the variable returns to scale specification might be more suitable for our problem (Rodríguez Díaz *et al*., 2004). Nevertheless, a comparison of both scores is interesting because it provides information on scale efficiency (Coelli *et al*., 2002).

3.2 Defining drainage water reuse scenarios

As mentioned in section 2, drainage water reuse can either increase the quantity of water available for use or can lead to water savings (Hundertmark & Salman, 2004). By using drainage water (either directly if of good quality, or blended if not) part of the required water demand can be replaced, leading to a net decrease in freshwater requirements at scheme level. However, to study the impact of water reuse on individual farmers it is necessary to identify meaningful scenarios that are based on valid and realistic assumptions.

In this study, the water reuse scenarios are straightforward and based on examples from the literature. Four different levels of water savings, which could possibly be obtained by the reuse of drainage water, are simulated, namely 5, 10, 15 and 20 per cent. At these levels, it is assumed that crop growth is still not adversely affected and that there is no accumulation of salts in the soil. A recent study by Corwin *et al*. (2008) supports the sustainability of drainage water reuse. Moreover, the levels of water reuse are in accordance with the drainage water reuse levels reported by Hundertmark and Salman (2004) in Egypt and with those reported by Zulu *et al*. (1996) in Japan. It is assumed that the introduction of drainage water reuse constitutes a technology shift by which farmers save fresh water without experiencing reduction on output. Under each scenario, the farm-level efficiency measure can be calculated again using the new water-use levels and keeping all other inputs and outputs of the farms constant.

3.3 Measuring changes in productivity: Malmquist productivity index

The productivity growth for an individual producer can be measured by the Malmquist index as improved efficiency relative to the benchmark frontier. Thus, the Malmquist index for productivity growth can easily be expressed in DEA efficiency measures (Odeck, 2007). In practice, the Malmquist index provides an assessment of productivity growth by measuring the change between two data points, where a data point consists of inputs and output. The Malmquist index is then calculated by taking the ratio of the distance of each data point relative to a common technology. This common technology is defined as the efficiency frontier derived from the DEA based on the sample data (Fraser & Hone, 2001).

We use the Malmquist productivity index to evaluate the changes in efficiency of farms due to the introduction of drainage water reuse. The index uses the VRS and CRS efficiency measures that are calculated in DEA models for two time periods (i.e. the current period and the simulated period after the introduction of the drainage water reuse scheme) to determine the resulting changes in the productivity of farms as production units. As explained in the previous section, drainage water reuse can be simulated by reducing the water input in the DEA model and keeping all other inputs and the output of the farms constant.

Theoretically, changes in productivity can be a combination of technological change and changes in the relative efficiency. This difference between the effects of technical change and changes in the relative efficiency is graphically illustrated in figure 1. The figure shows five decision-making units or farms (A, B, C, D, E) employing two inputs, for example water and labour. The original efficiency frontier (F1) is formed by farms A, B and C because these farms use a minimum set of inputs to produce output. In this figure technological change is illustrated by a shift of the efficiency frontier from F1 to F2 (assuming that efficient farms will remain efficient after having benefited from the technology change). Changes in relative efficiency can be seen as farms approaching the frontier (D to D* and E to E*). The Malmquist index incorporates both the changes in relative efficiency of the farms and the shift of the production frontier with which each farm is compared. More detailed information on the calculation of the Malmquist index can be found in Thanassoulis (2001) and Coelli *et al*. (1998).

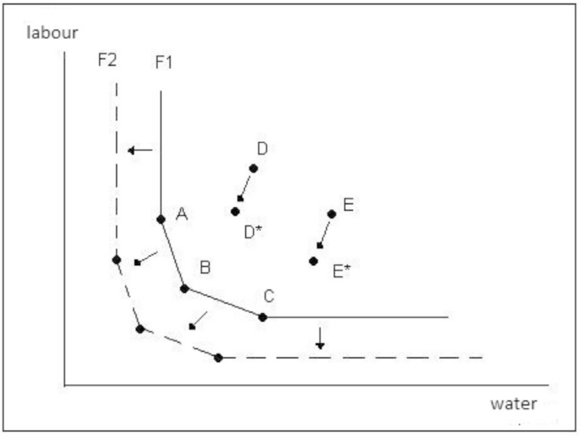

Figure 1: Graphical deconstruction of productivity change in: technological change (shift from F1 to F2) and changes in relative efficiency (shift from D to D* and E to E*)

3.4 Data collection and study area

Data were collected from farmers on small-scale irrigation schemes situated in Zeerust Municipality (North-West Province, South Africa) from July to September 2005. Because of the low levels of economic development and high levels of unemployment in the area, small-scale irrigation is of strategic importance for poverty reduction.

Questionnaires were used to collect data. In total 60 farmers were interviewed, from 13 small-scale irrigation schemes in the Zeerust Municipality. Random sampling was applied in selecting schemes and individual farmers, but representativeness was maintained by adapting the number of respondents at each scheme to the number of farmers operational in the schemes. Information was gathered on the irrigation schemes, household characteristics, farm activities, quantities and costs of inputs used in production (capital, variable and overhead), quantities and value of output, quantity of water consumed and irrigation practices. It was observed that the irrigation schemes in the study area were almost entirely used for vegetable crops. Beetroot, spinach, onions and carrots are widely planted and produced by 70–90 per cent of the farmers. The irrigation technology used by the farmers is usually uniform within a scheme. Furrow irrigation is the most frequently used method, with 40 per cent of the sample farmers adopting it. The use of hosepipes and bucket irrigation accounts for 20 and 33 per cent respectively. These techniques are typically used in food garden schemes. Variation in input use and output produced is considerably large. The range in plot size, from less than 100 m^2 to 2.8 ha, is obviously a reason for this. Generally, farmers seem to use a low input strategy. The inputs considered in the efficiency analysis included land (hectares), irrigation water use (m^3), labour (man days), fertilisers (costs) and pesticides (costs). The total output was converted into monetary terms using local market prices. The value of output and expenditure on inputs were calculated in rand and converted into US$. Statistics of the inputs and outputs used in the calculation of the DEA model are presented in table 1.

Table 1: Descriptive statistics on output produced and inputs used per farm (n=59)[1]

	Unit	Average	St. dev.	Minimum	Maximum
Output	US$	423.5	1706.7	22.6	13114.9
Inputs:					
Labour expenditures	US$	43.6	114.3	7.4	900.9
Expenditure on pesticides	US$	10.8	12.3	0.0	54.1
Expenditure on fertilizers	US$	9.6	13.7	0.0	72.2
Expenditure on fuel	US$	23.2	139.3	0.0	1082.9
Water use	m^3	1287.0	3299.0	82.9	22150.0
Land use	ha	0.2	0.4	0.01	2.8

[1] Note: the average ZAR/US$ exchange rate for the period July–September 2005 was used for conversion: 1 ZAR = 0.1504US$ (source: IMF, 2006).

4 RESULTS AND DISCUSSION

4.1 Current technical efficiency in irrigation schemes

Figure 2 shows the cumulative distributions for the different efficiency measures. Average technical efficiency was 0.51 under CRS and 0.84 under VRS specification. About 14 per cent and 39 per cent of the farms in the sample were identified as technically efficient under the CRS and the VRS specifications respectively (see Speelman *et al.*, 2008a for more details). These results show that at present substantial technical inefficiencies occur among smallholder irrigators in the area. This is in accordance with several other studies (Speelman *et al.*, 2008b; Perret, 2002; Shah *et al.*, 2002; IPTRID, 2000) concerning the poor performance of this type of irrigation scheme in South Africa. Furthermore, the large difference between the CRS and VRS measures indicates that scale inefficiencies are significant and that most farms are not operating at the optimal scale.

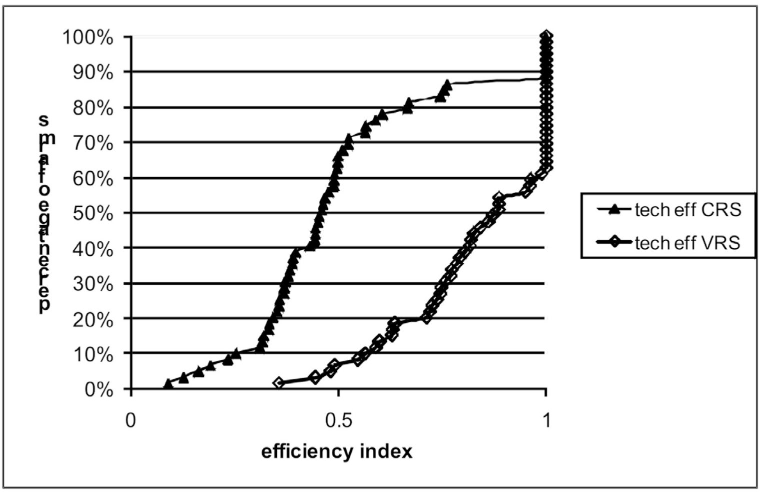

Figure 2: Cumulative distribution of efficiency indices (CRS and VRS) for farmers (n=59)

4.2 Simulations of drainage water reuse

The effect of the water savings resulting from the introduction of drainage water reuse is expressed by the Malmquist productivity index. Results are summarised in figure 3. In this figure the Malmquist indices are divided into different categories of change compared to the original situation and the share of farmers within each category is shown for the different water reuse scenarios. When water use is reduced by 5 per cent the productivity increases by 1.6 per cent on average. More than 50 per cent of the farms experience a productivity gain between 0 and 2.5 per cent, while about 20 per cent of the farms experience a gain between 2.5 and 5 per cent, and 6 per cent of the farms improved productivity with 5 per cent; 16 per cent of the farms on the other hand did not improve their productivity despite saving freshwater.

The share of farms without productivity improvements fall to 13, 10 and 8 per cent when water savings increase to 10, 15 and 20 per cent respectively. With a 10 per cent reduction in water use, productivity increases are more equally spread between 0 and 10 per cent. The average increase in productivity with this scenario is 3.4 per cent. If water use is further decreased, productivity gains increase. A majority of the farms show an increase between 2.5 and 10 per cent, with the average increase in productivity being 5.3 per cent. Finally, when water use is reduced by 20 per cent, nearly 40 per cent of the farms increase productivity by 5 to 10 per cent and the average increase is 7.4 per cent.

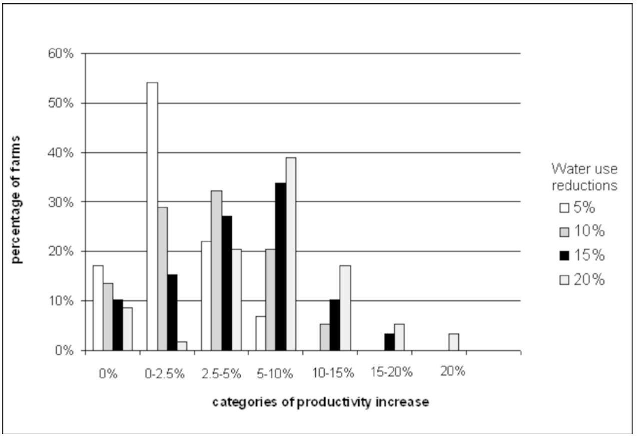

Figure 3: Distribution of farms over categories of total productivity change due to different levels of reduction of water use (n=59)

Figure 3 also shows that the more water is saved, the more the impact on the Malmquist index increases. The change in productivity in this case should be considered as technological change, because the efficiency frontier is shifted together with the position of the production units. Moreover, because the simulation was constructed in such a way that every farm establishes the same percentage reduction in water use, the pure technical efficiency change (relative to a VRS technology) is zero.

CONCLUSION

This paper simulates the effect of water savings by drainage water reuse on the farm efficiency for the case of small-scale irrigators in North West Province in South Africa. Firstly, DEA is used to determine the current technical efficiency of the small-scale irrigators. The results indicate that the mean technical efficiency under the CRS and VRS specifications is 51 and 84 per cent, respectively; the large difference between the two being a sign of substantial scale inefficiencies.

Then the introduction of drainage water reuse is simulated by reducing the input of fresh water, keeping the other inputs and the output constant. Four levels of water savings (5, 10, 15 and 20 per cent) were simulated. The results confirm that it is important to use a systems approach to evaluate efficiency changes. The effect of a certain reduction in water use depends on the entire input-output matrix of each farm and on the changes in the efficiency frontier. It is obvious that the more water is saved, the higher the average increase in productivity will be. Nevertheless, for most farms the percentage increase in productivity is smaller than the percentage reduction in water use. This demonstrates that water use is only one aspect of productivity. Furthermore, the fact that the effect is not the same for all farms indicates that farmers manage water differently.

This paper is a first attempt to calculate the impact of drainage water reuse on farm efficiency levels based on DEA and the Malmquist index. Although the potential of this approach is already shown here, for practical purposes more sophisticated scenarios should be used. In this paper the simulated water reuse was the same for all schemes. In reality though, the achievable level of reduction depends on the soil type, the crops to be grown, the agro-climatic conditions and the composition of the irrigation and drainage water. These conditions will vary between and even within schemes. If such information is available, this kind of specificity can easily be introduced in the DEA. Furthermore, with knowledge of the water composition the simulations could take into account the effects of different levels of drainage water reuse on crop growth and output. From this paper it is nevertheless clear that using the Malmquist index is an interesting way to evaluate the efficiency effects of the introduction of drainage water reuse.

NOTES

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