

SIMULATION OF THE EFFECTS OF WATER PRICING SCENARIOS ON SMALLHOLDER IRRIGATORS IN SOUTH-AFRICA

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ABSTRACT

The growing water scarcity worldwide puts pressure on irrigation systems as main consumptive user to improve performance. In developing countries, where today agricultural water use is often still heavily subsidised, a tendency exists of introducing water pricing policies to stimulate rational water use. The exact impact of water pricing policies in terms of water saving or its effect on the farmers' production systems remains unknown. This study introduces a new two-stage method that allows estimating at farm level the effects on the agricultural production process and water demand of introducing or raising a water price. In the first stage the technical efficiency frontier is constructed and the technical and allocative efficiency levels of each farm are calculated. This representation of the technology is used in the second stage in a profit maximization model. Applying the method to small-scale irrigators in South Africa, it is shown that water demand of farmers is quite responsive even to small changes in the water price. Furthermore, introduction of a water price is found to significantly decrease farm profit, which is particularly problematic for poor farmers.

KEY WORDS

water pricing, agricultural water use, data envelopment analysis, South Africa

1. Introduction

Irrigation systems are the main consumptive users of water at world level. Due to the growing water scarcity the sector experiences increasing pressure to release water for other uses and to find ways in which to improve performance ([1], [2], [3], [4]). The apparent misuse and waste of irrigation water in the context of low and subsidised water prices, therefore causes many to advocate a more prominent role of economic incentives in encouraging efficient water use ([5], [6], [7], [8], [9]). In this respect, irrigation water pricing is often regarded as an appropriate tool to achieve more efficient water use. Increasing the price of irrigation water or simply introducing a price is believed to have two important positive effects. Firstly, it will make consumers aware of the scarcity, creating a new respect for water, which

should improve management efficiency and secondly it provides incentives to farmers to rethink crop choices, stimulating the shift to more profitable crops ([10], [11], [8]). However, rises in water prices could lead to an overall reduction of a country's agricultural production, endangering the goal of securing food self-sufficiency. As a result prices for urban consumers may increase, occasioning increased imports and losses of market shares for local irrigating farmers whose agricultural income would tend to decrease. The effect on rural development is expected to be negative ([12], [5]). In addition authors like [13], [14] and [15] expect only a limited water saving effect because of low elasticities of demand for irrigation water. Finally there are historical, social and even religious dimensions linked to the introduction of water prices ([16]).

Taking into consideration the possible disadvantages and the limited effect water pricing scenarios might have on water saving, it is clear that developing methods and techniques that allow estimating the effects of water pricing on the agricultural production process and water demand, as accurately as possible, are very important ([3]). Due to the importance of the issues raised above, much research has been done in this area. For example [13], [17], [14], [18], [15] and [19] have used linear programming models to predict changes in cropping patterns resulting from different water pricing scenarios. From these changes they are able to deduce adjustments in water use and use of other inputs. A disadvantage of these methods is that they use predetermined fixed ratios between inputs and outputs and that they work at aggregated level assuming that all farmers are the same.

A novel method that allows estimating the effect of water pricing at farm level and that takes into consideration possible substitutions between inputs, is therefore proposed in this study. This method provides insight in the water saving effects of water pricing but also environmental effects (use of fertilizers and pesticides) and socio-economic effects (labour use, effect on farm profit and total agricultural output) are evaluated. This simulation is very relevant for smallholder irrigators in South Africa, where water subsidies will gradually decrease and farmers will have to pay to ensure cost recovery ([20]). Given the role these small-scale irrigation schemes play in providing a livelihood for rural

households it is important to determine the exact impact of this change on the irrigation water use and on the farmers' production system.

2. Methodology

2.1 Measuring efficiency with DEA models

The first step in this study consists of determining the production frontier and the current technical and allocative efficiency levels of farms in the sample using DEA. Technical efficiency (TE) is defined as 'the ability of a farm to use minimum feasible amounts of inputs to produce a given level of output' ([21]). Allocative efficiency (AE) on the other hand, refers to the degree to which inputs are used in optimal proportions, given the observed input prices and the value of the outputs produced.

When calculating technical efficiency using DEA, a production frontier is constructed and efficiency measures are obtained simultaneously. This is done by solving a sequence of linear programming problems, one for each farm. In this way the frontier obtained is formed by actual observations and envelops the observed input and output data of all farms. An implicit assumption of the DEA models used in this study is that returns to scale are constant and thus farms are believed to operate at an optimal scale ([22]). The formulas and a detailed description of the DEA model used can be found in [21].

A second characteristic to capture is the level of farms' success in choosing the optimal set of inputs given the input prices. This is done by calculating the allocative efficiency. Based on the technical and economic efficiency (EE) the allocative efficiency can be determined residually as $AE=EE/TE$. Economic efficiency for a case with K inputs and M outputs for N farms, is calculated in two steps. First a cost-minimizing vector of input quantities given the input prices is determined using the model from eq. 1:

$$\min_{x_i^*, \lambda} w_i' x_i^*, \quad (1)$$

subject to

$$\begin{aligned} -y_i + Y\lambda &\geq 0, \\ x_i^* - X\lambda &\geq 0, \\ \lambda &\geq 0 \end{aligned}$$

where w_i is a vector of input prices for the i-th farm and x_i^* (which is calculated) is the cost-minimizing vector of input quantities for the i-th farm, given the input prices w_i and the output levels y_i . λ is a vector of N constants, x_i and y_i , are column vectors with the input and output data for the i-th farm. X is a K by N matrix and Y a M by N matrix with respectively all input and output data for all N farms in the sample. In the second step EE of the i-th farm is calculated as the ratio of the minimum cost to the observed cost (eq. 2):

$$CE = w_i' x_i^* / w_i' x_i \quad (2)$$

With the allocative and technical efficiency of each farm calculated, a model to estimate the impact of changes in the water price can now be constructed.

2.2 Simulating impact of different water prices

Several authors, listed in the introduction, have used linear programming models to estimate water demand. Based on one or more objective functions, these models predict changes in cropping activities and linked to this, changes in water use at different water price levels. This type of models typically uses a number of cropping alternatives in which the levels of input use and the output produced are fixed. As a consequence, substitutions between different inputs within an alternative are not captured at all, or only in a very static way (if different input-output sets for the same crop are defined). Substitution between water and other agricultural inputs is however reported as an effect of increasing water prices by [23] and [24]. Another shortcoming in most of these models is that they are based on average technology and implicitly make the assumption that all farms react in the same way. This combination of the use of average technologies and the simplified fixed resource constraints leads to overly abrupt changes in the price response ([25]).

The approach suggested in this paper uses the information from the efficiency analysis above in modelling the effect of water price changes at farm level. The frontier and efficiency measures are used as a representation of the production technology. In this way the weaknesses of the classical approaches, discussed above, are overcome. In addition, by incorporating the occurrence of inefficiencies in the price responses, simulations should better reflect reality ([26]). The rationale is similar to that of [25] when they incorporate frontier technology and inefficiencies in the mathematical programming of a sector model. By introducing the efficiency information, representation of the production technology is improved. The underlying assumption for this second step is that farmers will adjust their water use and input mix in response to the introduction of water charges, because relative prices have changed. In the short run this will not have a direct effect on their overall levels of efficiency as they were defined above. This is confirmed in a study by [27]. When they decomposed productivity changes in Greek hospitals between two time periods, they were able to clearly distinguish the effects of changes in allocative and technical efficiency, changes in production technology and changes caused by shifts in input prices. In this way they showed that shifts in input prices cause changes in input use without changing allocative efficiency.

The simulation model of this study is presented in eq. 4 to eq. 18. In this model w'_{new} and w' are the new and old price vector, respectively, for each farm and $xsim_i^*$ and x_i^* the new and old cost-minimizing vector of input quantities for the i-th farm. $xsim_i$ is the simulated input vector, which retains each farm's technical and allocative efficiency and x_i is the original input vector. For all these

vectors subscripts “ $k1$ ”, “ $k2$ ” indicate one of the non-water inputs, while subscript “ wa ” indicates water input. $ysim_i$ and y_i are the simulated and original outputs. λ_1 and λ_2 are vectors of constants. θ and EE are the technical and the economic efficiency level, determined in the first step for each farm. Finally, X_{fron} and Y_{fron} are parameters that are equal to the observed input vector and output vector of farms for which technical efficiency was found to be 1 in the first step:

$$\underset{\lambda_1, \lambda_2, xsim_i^*, xsim_i^*, ysim_i}{Max} \quad ysim_i - w'_{new} xsim_i, \quad (4)$$

subject to

$$-ysim_i + Y_{fron} \lambda_1 \geq 0, \quad (5)$$

$$xsim_i^* - X_{fron} \lambda_1 \geq 0, \quad (6)$$

$$-ysim_i + Y_{fron} \lambda_2 \geq 0, \quad (7)$$

$$\theta xsim_i - X_{fron} \lambda_2 \geq 0, \quad (8)$$

$$\frac{w'_{new} xsim_i^*}{w'_{new} xsim_i} = EE, \quad (9)$$

$$ysim_i \leq y_i, \quad (10)$$

$$xsim_{wa,i} \leq x_{wa,i} \quad (11)$$

$$xsim_{k,i} \leq xsim_{k,i}^* \quad \forall k, \text{ if } x_{k,i} \leq x_{k,i}^* \quad (12)$$

$$xsim_{k,i} \geq xsim_{k,i}^* \quad \forall k, \text{ if } x_{k,i} \geq x_{k,i}^* \quad (13)$$

$$w'_{new} xsim_{k1,i} \leq w'_{new} xsim_{k2,i} \quad \forall k, \text{ if } w' x_{k1,i} \leq w' x_{k2,i} \quad (14)$$

$$w'_{new} xsim_{k1,i} \geq w'_{new} xsim_{k2,i} \quad \forall k, \text{ if } w' x_{k1,i} \geq w' x_{k2,i} \quad (15)$$

$$\frac{xsim_{k,i}}{x_{k,i}} \geq \frac{xsim_{wa,i}}{x_{wa,i}} \quad \forall k \quad (16)$$

$$\lambda_1 \geq 0 \quad (17)$$

$$\lambda_2 \geq 0 \quad (18)$$

The objective function maximizes the gross margin of the farmers (Eq. 4). To reflect the situation that farmers start adjusting from an existing input mix, the original vectors x_i and y_i are used as starting values in the simulation. Equations 5 to 18 are the constraints in the model. Eq. 5 to 9 and 17 and 18 form the representation of the technology found in the first step and incorporate the inefficiency levels of the farmers. Eq. 9 in combination with 5 and 6 equals the economic efficiency given the new prices with the economic efficiency under the original prices, while eq. 7 and 8 make sure that the technical efficiency is maintained. Eq. 10, 11, 12, 13 and 16 are based on economic theory. For instance eq. 10 and 11 imply that a rise in the price of water will not lead to a rise of output or the use of water, respectively, and eq. 16 adds to this that the relative use of the input will decrease. Eq. 14 and 15 finally ascertain that farmers' preferences for using certain inputs are maintained.

A graphical illustration of the method using a simple numerical example is presented in figure 1. In the starting situation Decision Making Units (DMUs) A-H use two

inputs (X1 and X2) to produce a single output (Y). All units face the same input prices (P1 and P2), which are equal to 3 units for both inputs (cost boundary 1). The technical efficiency frontier is formed by DMUs A, B, C and D. Moreover at the original prices DMU A is allocative and economic efficient, with cost boundary 1 tangent to the technical efficiency frontier.

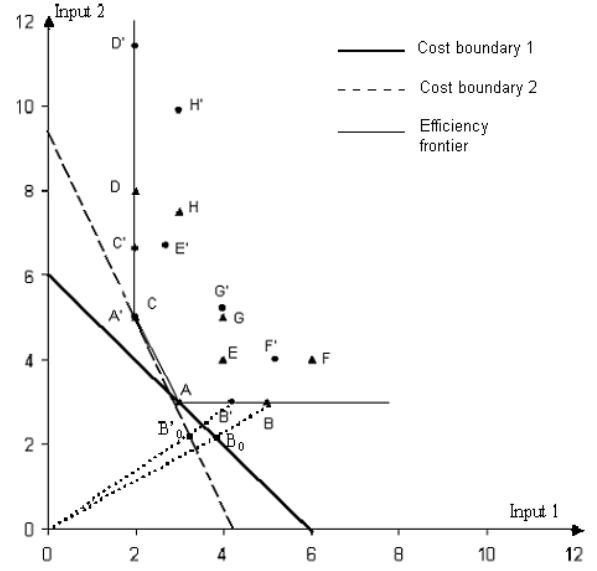


Figure 1. Simulating effect of relative price changes in a simple numerical example

Assume now that the price of input 1 increases to 7 for all units. This change in relative prices of inputs 1 and 2 causes the slope of the cost boundary to change (cost boundary 2). As a result technical efficient DMUs will move on the efficiency frontier maintaining their level of economic efficiency, which reflects an inherent characteristic of these DMUs namely the way they perceive prices. DMU A for instance moves from point A to point A', where the new cost boundary is tangent to the frontier. DMU B moves from point B to point B' and the preservation of the economic inefficiency here can be graphically shown as $OB/OB_0 = OB'/OB'_0$. Summarizing, technical efficient DMUs move along the frontier, maintaining their economic inefficiency level, but changing the input mix. Similar to the DMUs on the frontier DMUs with a TE smaller than 1 stay at the same technical and economic efficiency level.

2.3 Data collection

Data was collected from small-scale irrigation schemes situated in Zeerust Municipality (North-West Province, South Africa) from July to September 2005. Farmers in these schemes mainly produce vegetables. Questionnaires were used to collect data, with a total of 60 farmers interviewed, spread over 13 small-scale irrigation schemes. Random sampling was applied to select schemes and individual farmers, but representativeness was maintained by matching the number of respondents from

each scheme with the number of farmers operational within them.

During the interviews information was gathered on quantities and costs of inputs used in production, quantities and values of outputs and the quantity of water consumed. Expert knowledge of extension staff was used as a supplement to the recollections of the farmers, something that was particularly helpful for the estimation of the water use and the prices of their produce. Using the quantities and corresponding prices of the different outputs a monetary value for the total output was calculated. The inputs considered in the efficiency analysis include land, irrigation, labour, fertilizers and pesticides (table 1). Although the sample is relatively small, this case study reflects the typical situation of many rural areas in South Africa and thus provides interesting insights. Moreover the sample suffices to demonstrate the possibilities of the methodology adopted.

Table 1
Descriptive statistics on outputs and inputs used in efficiency analysis

	Unit	Mean	St. dev.	Min.	Max.
Output	rand ¹	2816	11348	150	87200
Inputs					
Land	ha	0.16	0.40	0.01	2.8
Water	m ³	1287	3299	82.9	2215
Labour	man days	29	76	5.6	599
Expenditure on pesticides	rand	72	82	0	360
Expenditure on fertilizers	rand	64	91	0	487

3. Results and discussion

In the first step, the technical, economic and allocative efficiency measures are calculated. The average technical efficiency is 0.51, indicating that substantial inefficiencies occur in farming operations of the sample farm households. Allocative and economic efficiency are even lower, with average values of 0.26 and 0.14, indicating that farmers could considerably reduce costs by taking more notice of relative input prices when selecting input quantities. These low values can be linked to the reported poor economic performance of the small-scale irrigation schemes in South Africa ([28]).

Using the simulation model described in section 2 the original situation of South African smallholders, where water is a free input, is changed by introducing different water price levels (0.025R/m³, 0.05R/m³, 0.1R/m³, 0.2R/m³, 0.3R/m³, 0.5R/m³ and 1R/m³). In figure 2 classes of water saving are created and the share of farmers in each class is presented for the five water pricing scenarios. It is clear that already at low prices farms would start to considerably save water. Such results were also found by [29] and [30]. By allowing substitution between inputs in the model, water demand is clearly much more elastic then found by [13], [17] or [14]. The

result is furthermore not surprising given the big scope for improvements in water use efficiency, which can be deduced from the low water use sub-vector efficiencies found by [31]. At higher water prices, water saving also increases because farms that are not profitable anymore will stop producing.

The finding of [14] that farmers' response can be very different, depending on the elasticity of their demand, is also confirmed here.

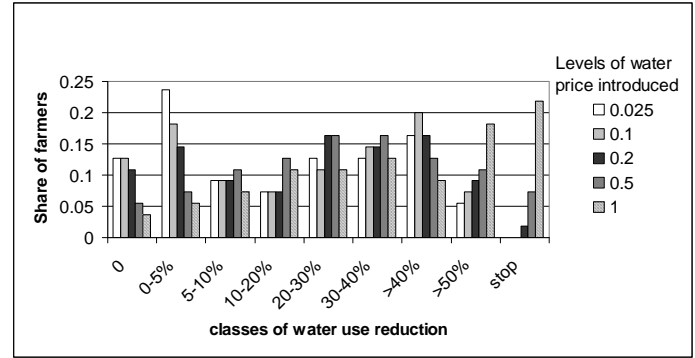


Figure 2. Classification of the reduction in water use under different water pricing scenarios

If water use efficiency is expressed in profit/m³, the evolution under different water pricing scenarios can be monitored in figure 3, where the average efficiency is expressed in R/m³. It shows that introduction of a water price of 0.025R/m³ immediately leads to an increase in water use efficiency of about 20%. However, further increases in the water price have only limited additional effects on the average efficiency. This is because the higher water prices do not only decrease water use but also severely affect the profit of the farmers.

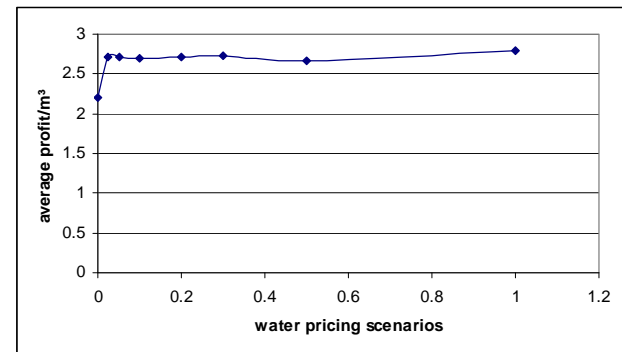


Figure 3. Evolution of water use efficiency at different water price levels

Figure 4 shows the effect of the water pricing scenarios on aggregated use of the individual inputs. Although not all farms react in the same way, there is a tendency of substitution between labour and water at the lower price levels. This was also reported by [23]. The overall use of other inputs on the other hand decreases together with the water use, a result found in most studies. Relative use of the non-water inputs nevertheless

¹ At the time of the data collection the exchange rate was 1 Rand = 0.1504 US\$

increases. At higher water prices an additional reason for the decreases in the use of all inputs is that farms go out of production.

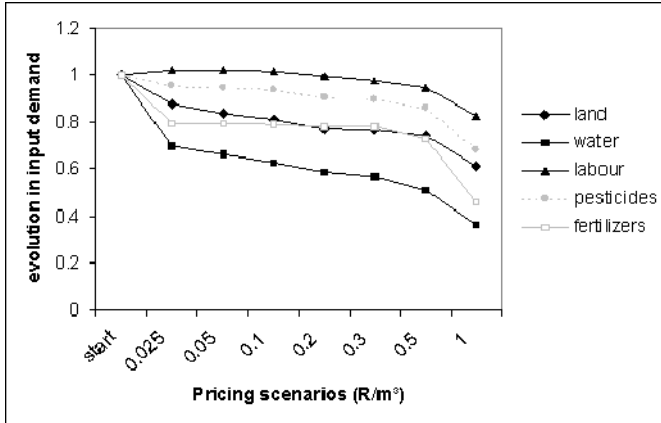


Figure 4. Evolution of overall input demand at different water price levels

In figure 5, total profit (in terms of gross margins) under different water pricing scenarios is compared with that in the actual situation. Gross margins appear to be quite stable at the lower price levels. At these levels irrigation water forms only a small part of the costs and as a consequence has only limited effect on gross margins. This was also mentioned by [16].

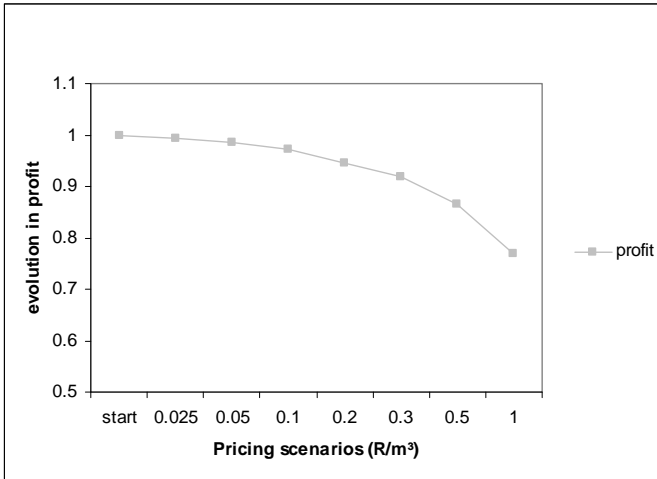


Figure 5. Evolution of profit (gross margin) at different water prices

Figure 6 looks at the evolution in profit on an individual level and presents the cumulative distribution functions for the loss in profit at each price. For instance, at a price of 0.1R/m³, reduction in profit for 90% of the farmers is less than 18%. Comparison of figure 5 and 6 shows that at each level of price introduced, in terms of percentage the loss in profit for most of the farms is higher than the total percentage of figure 5. In other words looking at the evolution of total profit of the sector does not give an adequate picture of the effect of the introduction of a water price because information on

individual farms is lost. Similar to [19] and [32] a significant loss of farm income is found for many individual farms.

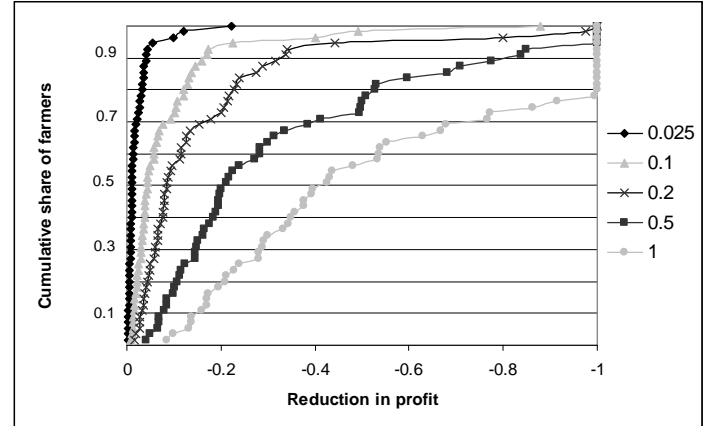


Figure 6. Cumulative distribution of reduction in profit for different water pricing scenarios

4. Conclusion

Water pricing is often seen as an important tool to improve efficiency of water use. However, several authors expressed concerns on the limited effect in terms of water saving and the even negative economic and social side effects of this policy. Given the increasing pressure to release water for other uses and to improve irrigation performance, there is an urgent need for methods that allow predicting the effects of water pricing policies. This study proposes a novel simulation technique to simulate the effect of changes in water price. First a simple numerical example shows that the results of the simulation model are in line with classical economic theory, with a price change causing a change in the relative use of the inputs. When applied to the case of South Africa, an important finding is that farmers are quite responsive to even small changes in water price. This can be explained by the low water use sub-vector efficiencies reported in an earlier study ([31]) and by the possibility of input substitution incorporated in the model. Another key finding which was also reported by other studies is the magnitude of the adverse effect on farm profitability. From a development perspective it is worrying that it seem to be the smaller farms in terms of output (mostly the poorer farmers), which are affected most and which at higher water prices even stop producing.

Regarding the methodology, from the above it is clear that the use of observed technology frontiers in simulation models can clearly improve estimation of price change effects. Changes are less abrupt and by incorporating the occurrence of inefficiencies at farm level, simulations should more closely reflect reality. A limitation of the current model is that it currently assumes constant returns to scale in the definition of the production frontier. Models assuming variable returns to scale can be

developed. Further research could also focus on developing a model that works with frontiers on crop instead of on farm level to predict changes in cropping patterns explicitly.

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