A new methodology for assessing the impact of water-pricing scenarios: case study of small-scale irrigation schemes in South Africa

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Abstract—**Worldwide growing water scarcity has increased the call for economic instruments to stimulate rational water use in agriculture. In addition cost-recovery is now widely accepted as a cornerstone of sustainable water management. As a consequence now in developing countries, where currently agricultural water use is often still heavily subsidized, a tendency exists of introducing water-pricing as a policy to achieve more sustainable water use. The exact impact of water pricing policies on irrigation water use or on the farmers' production system is however mostly unknown. A new two-stage methodology that allows estimating at the farm level the effects of introducing or raising a water price on the agricultural production process and water demand is introduced in this study. The first stage comprises the construction of a technical efficiency frontier and the calculation of the technical and allocative efficiency levels of each farm. This representation of the technology is used in the second stage in a profit maximization model. As an example the method is applied to the case of 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. Moreover, the introduction of a water price is shown to significantly decrease farm profit. This appears to be mainly a problem for the poorer farmers**

Keywords— **water-pricing, water savings, irrigation, data envelopment analysis, South Africa.**

I. INTRODUCTION

Irrigation is a main consumptive user of water at world level. Due to the growing water scarcity irrigators experience increasing pressure to release water for other uses and to find ways in which to improve performance ([1], [2]). Efficient use of water resources is therefore considered a fundamental target for farmers and water management ([3], [4]). In this respect, the apparent misuse and waste of irrigation water, in the context of low and subsidised water prices, causes many ([5], [6], [7], [8], [9]) to advocate a more prominent role of economic incentives in encouraging efficient water use.

Irrigation water pricing is often regarded as a good tool to achieve efficient use ([10]). 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 provide incentives to farmers to rethink crop choices, stimulating the shift to more profitable crops ([11], [12], [8]). The effect of irrigation rates on efficiency might however be insignificant if they represent too small a proportion of the total production costs. Another reason reported to expect only limited effects is the low elasticity of demand for irrigation water ([13], [14], [15]). Moreover, according to [16] and [5] rises in water prices are not without risk: They could lead to an overall reduction in a country's agricultural production, endangering the goal of securing food self-sufficiency. They could also lead to higher prices for urban consumers resulting in increased import and loss of market share for local irrigating farmers. Finally they could lower agricultural income with negative effect on rural development. Moreover increasing or introducing water charges is a sensitive issue in many parts of the world, involving historical, social and even religious dimensions ([17)]. Taking into consideration the disadvantages and the possible limited effect water pricing scenarios might have on water saving, it is clear that methodologies that allow to estimate as accurately as possible, the effects on the agricultural production process and water demand are important ([3]). Much research has been done in this area. For example [13], [18], [14], [19], [15] and [20] have used linear programming models to predict changes in cropping patterns resulting from different water pricing scenarios. From these changes they then deduced water use and use of other inputs. A disadvantage of these methods is that they use predetermined fixed ratios between inputs and outputs and work at aggregated level assuming that all farmers act the same. Other authors like [21], [7] and [22] use econometric approaches to study the impact of water pricing. Although they model individual decisions they also neglect input substitution possibilities.

Therefore in this study a novel methodology is proposed. It allows estimating the effect of water pricing at farm level and takes into account possible substitutions between inputs. Comparison of the simulated level of water use with the current one offers an interesting insight in the water saving effect of the introduction of water charges. In addition environmental effects (use of fertilizers and pesticides) and socio-economic effects (labour use, effect on farm profit and total agricultural output) can also be assessed. The methodology is applied to a sample of 60 small-scale irrigators in North West Province, South Africa. This is a relevant case study because in South Africa the principle of water as an economic good is now incorporated in the water law, thus levying charges on its use. For farmers at small-scale irrigation schemes this is a new challenge, because up to now their water use is entirely subsidized. In the near future, these subsidies will gradually decrease and farmers will have to pay for water to ensure cost recovery ([23]). As in most cases one of the expected benefits of this policy change is that water use efficiency will rise, but the exact impact on the irrigation water use or on the farmers' production system is unclear. Given the role these small-scale irrigation schemes play in providing a livelihood for rural households this impact might nevertheless be very important. Indeed, apart from creating employment opportunities, these schemes are believed to contribute to rural development by their potential to alleviate food insecurity and to generate additional income opportunities ([24], [25]).

II. METHODOLOGY

A. Measuring efficiency with DEA models

The first step in this study consists of determining the current technical and allocative efficiency levels of the farms in the sample using DEA. DEA is a nonparametric systems approach in which the relationship between all inputs and outputs is taken into account. In this study input-oriented measures were chosen to reflect local reality, where a decrease in the use of water is an underlying objective. Technical efficiency (TE) is then defined as 'the ability of a farm to use minimum feasible amounts of inputs to produce a given level of output' ([26]). 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. Economic efficiency (EE) finally is the product of allocative and technical efficiency and captures performance in both measures. In practice, economic and allocative efficiency can be calculated with only minor adjustments to the basic model for calculation of technical efficiency.

In DEA simultaneously a production frontier is constructed and efficiency measures are obtained. 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. For a case with K inputs and M outputs for N farms the technical efficiency θ for each farm is searched as follows:

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

subject to
$$\begin{aligned} &-y_i + Y\lambda \geq 0, \\ &\theta x_i - X\lambda \geq 0, \\ &\lambda \geq 0 \end{aligned}$$

where θ is a scalar and λ is an vector of 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. The value θ, a score always lying between zero and one, with a value of one indicating that the farm lies on the frontier and is efficient. An implicit assumption of the model described above is that returns to scale are constant and thus farms are operating at an optimal scale ([27]).

A second characteristic to capture is the 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 the allocative efficiency can be determined residually as AE=EE/TE. Economic efficiency itself is calculated in two steps. First a cost-minimizing vector of input quantities given the input prices is determined using the model from eq. 2:

$$Min_{x_i^*\lambda} w' x_i^*, \qquad (2)$$

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

where w_i is a vector of input prices for the i-th farm and x_i* (which is calculated by using linear programming) 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. The other symbols are defined the same as in eq 1.

In the second step economic efficiency (EE) of the i-th farm is calculated as the ratio of the minimum cost to the observed cost (eq. 3)

$$EE = w'_i x_i^* / w'_i x_i \qquad (3)$$

The frontier and efficiency measures calculated can now be used as a representation of the production technology in a model to estimate the impact of changes in the water price.

B. *Simulating impact of different water prices*

As shown in the introduction, linear programming models have been used extensively to estimate the effect of water pricing on 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. However, this type of models typically uses a number of cropping alternatives with fixed levels of input use and output produced. Consequently, substitutions between different inputs within an alternative are not captured at all, or only in a very static way by defining different input-output sets for the same crop as in [18], [15] or [20]. The authors [28] and [29] however report substitution between water and other agricultural inputs as an effect of increasing water prices.

Another shortcoming of 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. An improvement to this is the model by [14] that classifies farms into different farm types and looks at the impact on each one of them. The combination of the use of average technologies and the simplified fixed resource constraints nevertheless leads to overly abrupt changes in the price response ([30]). Econometric models for studying impact of water pricing by [21], [7], [22] on the other hand have the advantage of modelling individual farmers' land allocation choices, but these models also neglect the possibility of substitution between inputs.

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. In this way the weaknesses of both types of approaches discussed above can be overcome. In addition, by incorporating the occurrence of inefficiencies in the price responses, simulations should better reflect reality ([31]). The rationale is similar to that of [30] 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. Besides, the farm level accounting data to estimate the technology frontier are relatively easy to collect. An 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. It is assumed however that in the short run this will not have a direct effect on their overall levels of efficiency as they were defined above. A study by [32] confirms this assumption. 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 the technology of production and changes caused by shifts in input prices. Thereby 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 respectively the new and old price vector 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 maintains each farms' 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. $\lambda 1$ and $\lambda 2$ are vectors of constants. θ is the technical efficiency level and EE_i is the economic efficiency level which were determined in the first step for each farm. X_{fron} and Y_{fron} finally 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

$$\underset{\lambda 1, \lambda 2, xsim_i, xsim_i^*, ysim_i}{Max} \quad ysim_i - w_{new}^{'} xsim_i, \tag{4}$$

subject to

$$-ysim_i + Y_{fron}\lambda_1 \geq 0, \tag{5}$$

$$xsim_i^* - X_{fron}\lambda_1 \geq 0, \tag{6}$$

$$-ysim_i + Y_{fron}\lambda_2 \geq 0, \tag{7}$$

$$\theta xsim_i - X_{fron}\lambda_2 \geq 0, \tag{8}$$

$$\frac{w_{new}^{'} x_i^{'*}}{w_{new}^{'} xsim_i} = EE_i, \tag{9}$$

$$ysim_i \leq y_i, \tag{10}$$

$$xsim_{wa,i} \leq x_{wa,i} \tag{11}$$

$$xsim_{k,i} \leq xsim_{k,i}^* \qquad \forall \text{k, if } x_{k,i} \leq x_{k,i}^* \tag{12}$$

$$xsim_{k,i} \geq xsim_{k,i}^* \qquad \forall \text{k, if } x_{k,i} \geq x_{k,i}^* \tag{13}$$

$$w_{new}^{'} xsim_{k1,i} \leq w_{new}^{'} xsim_{k2,i} \qquad \forall \text{k, if } w' x_{k1,i} \leq w' x_{k2,i} \tag{14}$$

$$w_{new}^{'} xsim_{k1,i} \geq w_{new}^{'} xsim_{k2,i} \qquad \forall \text{k, if } w' x_{k1,i} \geq w' x_{k2,i} \tag{15}$$

$$\frac{xsim_{k,i}}{x_{k,i}} \geq \frac{xsim_{wa,i}}{x_{wa,i}} \qquad \forall \text{k} \tag{16}$$

$$\lambda_1 \geq 0 \text{ and } \lambda_2 \geq 0 \qquad \text{(17) and (18)}$$

The objective function of the model 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 of the model 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 respectively introduce that a rise in the price of water will not lead to a rise of output or the use of water and eq. 16 adds to this that the relative use of the input will decrease. Eq. 14 and 15 finally assure that farmers' preferences for using certain inputs are maintained.

Figure 1 shows how the method works using a simple numerical example showing eight Decision making Units (DMUs). These DMUs A-H use two inputs (X_1 and X_2) to produce a single output (Y). For simplicity it is assumed here that all units face the same input prices, equal to 3 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.

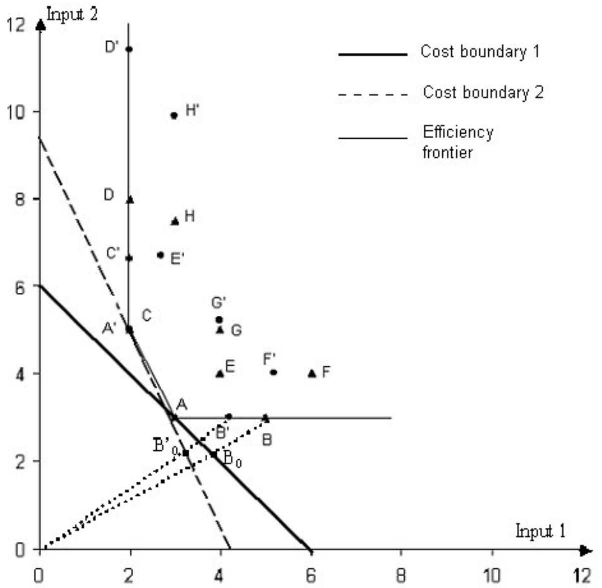

Figure 1: Simulating effect of relative price changes in a simple numerical example

We can now apply the model described above to estimate the effect of a price change of one of the inputs. 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 alter (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 the 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 $0B/0B_0 = 0B'/0B'_0$. Technical efficient DMUs move along the frontier, maintaining their economic efficiency level, but changing the input mix. Similar to the DMUs on the frontier, DMUs with a technical efficiency below one, stay at the same technical and economic efficiency level.

C. Data collection

Data was collected from small-scale irrigation schemes situated in Zeerust Municipality (North-West Province, South Africa) from July to September 2005. The farmers in these schemes use irrigation water mainly to produce vegetable crops. Like in most small-scale irrigation schemes in South Africa the irrigation water is still delivered for free. 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 the number of respondents from each scheme was matched 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. Because the farmers in the study area do not keep records of their farming activities, information gathered during interviews was based on recollections of farmers. 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. A monetary value for the total output was calculated using the quantities and corresponding prices of the different outputs. 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.

III. RESULTS AND DISCUSSION

In a first step the three efficiency measures described above (technical, economic and allocative efficiency) are calculated. Technical efficiencies range between 0.1 and 1 and 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 an average value of 0.32 and 0.14 respectively.

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

	Unit	Average	St. dev.	Minimum	Maximum
Output	rand[1]	2816	11348	150	87200
Inputs					
Land	ha	0.16	0.40	0.01	2.8
Water	m³	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

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

These scores suggest that farmers could considerably reduce costs by paying more attention to relative input prices when selecting input quantities. In South Africa such low values can be linked to the reported poor economic performance of the small-scale irrigation schemes in general ([22]).

The simulation model described in section 2 is now applied to the South African farm budget dataset. The original situation, where water is a free input, is changed by introducing different water price scenarios (0.025R/m³, 0.05R/m³, 0.1R/m³, 0.2R/m³, 0.3R/m³, 0.5R/m³, 1R/m³). Already at low prices farms start to save water considerably. This can be seen in figure 2, where the water savings per farm are divided into different classes and the share of farmers in each class is presented for each water pricing scenario. A similar finding was also reported by [21] and [22].

By allowing substitution between inputs in the model, water demand is clearly much more elastic then found by [13], [14], and [18]. The result is furthermore not surprising given the low water use efficiency found in a previous study [33]. In the absence of water pricing, the introduction of even a low water price gives farmers an incentive to use water more sparingly.

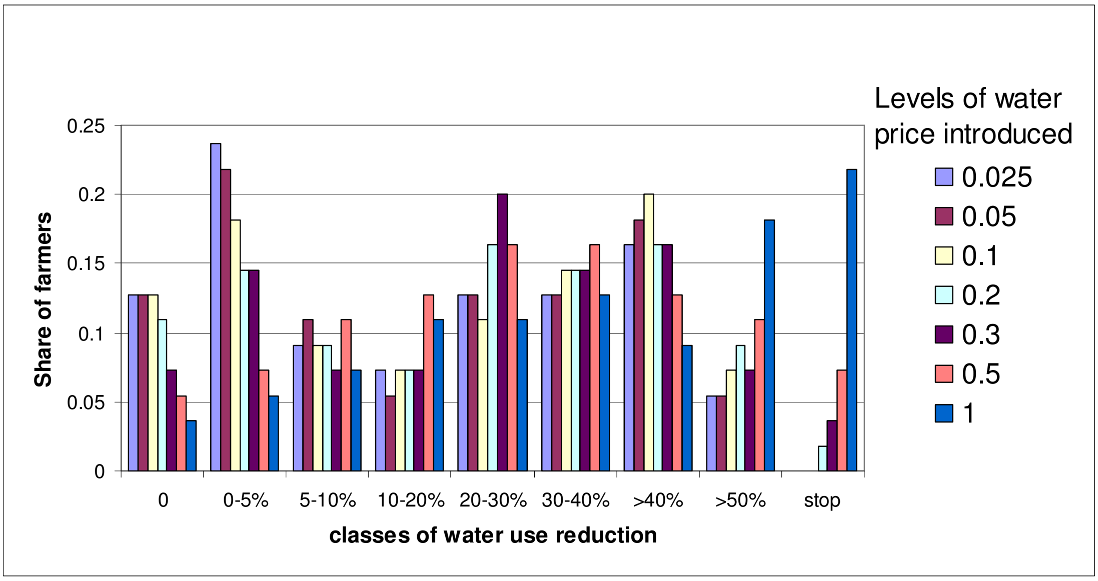

Figure 2. Classification of the reduction in water use under different water pricing scenarios

At higher water prices water saving also increases because some farms that are not profitable anymore could stop producing. The finding of [14] that farmers' elasticity of demand can be very different is also confirmed here, because clearly not all farmers have the same response.

Figure 3 shows the effect of the different water pricing scenarios on the aggregated use of the different inputs. The overall use of most inputs (land, pesticides, fertilizers) decreases together with the water use, a result found in most studies. This suggests that they are complementary inputs. However for labour the situation is different, although not all farms react in the same way. At the lower price levels, there is a tendency of substitution between labour and water. This finding was also reported by [28]. As expected from economic theory the relative use of the non-water inputs increases.

At higher water prices an additional factor for the decreases in the use of all inputs is the farms that go out of production. This happens when profits become negative due to the introduction of the water price and it is not possible anymore to counter this by adjusting the input mix.

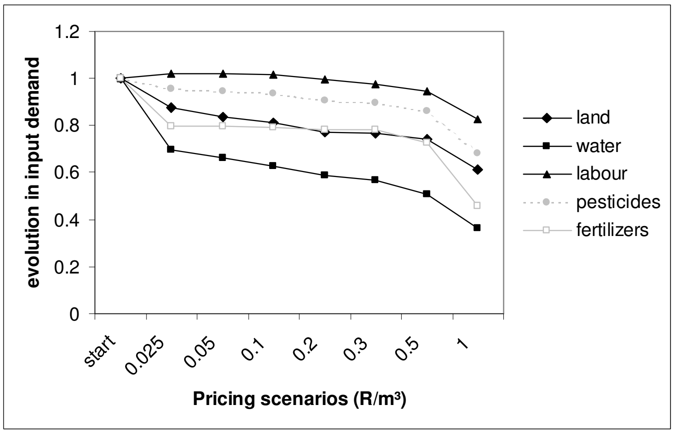

Figure 3. Evolution of overall input demand at different water price levels

Looking at the evolution of total output in monetary terms and at the total profit in terms of gross margins, these appear to be quite stable at the lower prices levels (figure 4). At these levels irrigation water forms only a small part of the costs and as a consequence has only limited effect on gross margins. Notwithstanding the fact that quite some farms stop producing as shown above, the effect on the reduction in total output, even at higher water prices, seems limited. This can be explained by the fact that mainly the less profitable farms that produce less output go out of business. The more profitable farms that produce more output and thus have more weight in total output, reduce output only a bit.

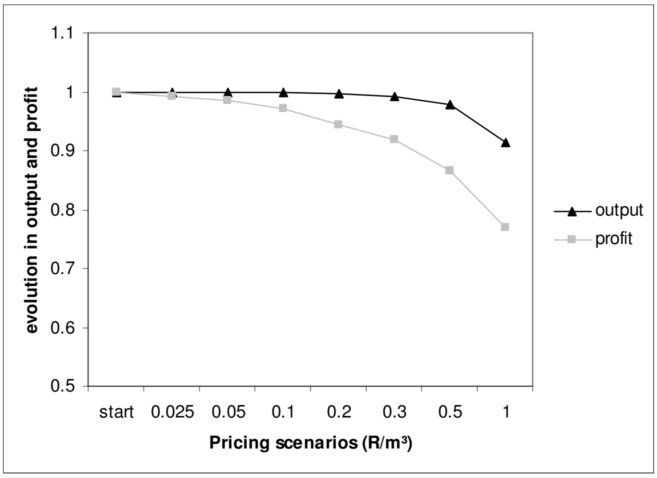

Figure 4 Evolution of total output (monetary terms) and profit (gross margin) at different water prices

This explication is also confirmed by figure 5. Here the cumulative distribution functions for the loss in profit at each price are presented. The distribution of the loss in profit for individual farms can be seen in this figure. By comparing figure 4 and 5, it can be seen that at each level of price introduced the loss in profit in percentage for most of the farms is higher than the total percentage of figure 4. For example at a price of 0.5R/m³ more than half of the farms has a reduction of profit above 20% (see figure 5), while the total profit decreases only with about 15%. In other words looking at the total profit of the sector does not give an complete picture of the effect of the introduction of a water price because information on individual farms is lost. Similar to [20] and [34] loss of farm income for many farms appears to be significant.

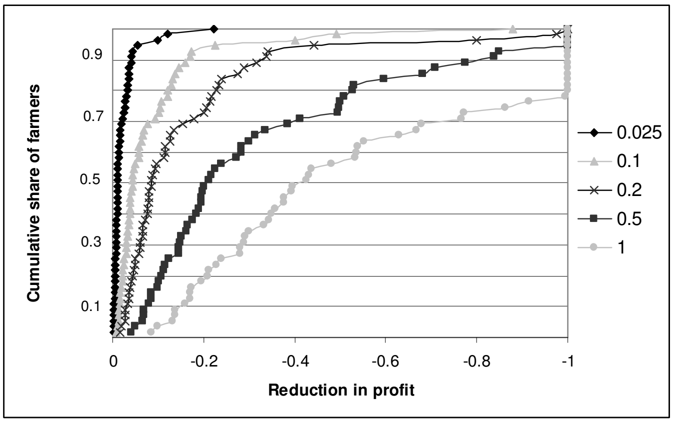

Figure5 Cumulative distribution of reduction in profit for different water pricing scenarios

IV. CONCLUSIONS

With the increased attention for cost recovery and given the increasing pressure to release water for other uses and to find ways in which to improve irrigation performance, water pricing is often seen as a good tool for the water sector. Several authors however have expressed concerns on the limited effect in terms of water saving and the even negative economic and social side effects of this policy. Therefore, there is an urgent need for methodologies to estimate the exact effects of different water pricing scenarios. This study proposes a novel method to simulate the effect of changes in water price. When applied to 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 efficiencies reported in an earlier study 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 appear to be the smaller farms in terms of output (mostly the poorer farmers), which are affected most and which at higher water prices are even expected to stop producing because they are not profitable anymore.

Regarding the methodology, from the above it is clear that the use of observed technology frontiers in simulation models can give interesting new insights when estimating the effects of price changes. Changes are less abrupt and by incorporating the occurrence of inefficiencies at farm level, simulations should more closely reflect reality. Further research could focus on developing a model that works with frontiers on crop instead of on farm level. In this way changes in cropping patterns could also be explicitly predicted.

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