TOWARDS QUANTIFYING THE ECONOMIC EFFECTS OF POOR AND FLUCTUATING WATER QUALITY ON IRRIGATION AGRICULTURE: A CASE STUDY OF THE LOWER VAAL AND RIET RIVERS

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Irrigation farmers in the lower reaches of the Vaal and Riet Rivers are experiencing substantial yield reductions in certain crops and more profitable crops have been withdrawn from production, hypothesised, as a result of generally poor but especially fluctuating water quality. In this paper secondary data is used in a linear programming model to test this hypothesis by calculating the potential loss in farm level optimal returns. The model is static with a time frame of two production seasons. Linear crop-water quality production functions (Ayers & Westcot, 1983; adapted from Maas & Hoffmann, 1977) are used to calculate net returns for the eight most common crops grown. Results show optimal enterprise composition under various water quality situations. Leaching is justified financially and there is a strong motivation for a change in the current water pricing system. SALMOD (Salinity and Leaching Model for Optimal irrigation Development) is the Excel Solver model used to derive the preliminary results, but is currently being developed further in GAMS (General Algebraic Modelling System). Useful results have already been obtained on which this paper is based. The ultimate aim for SALMOD is a mathematical model using dynamic optimisation, simulation and risk modelling techniques to aid in whole farm and system level management decisions to ensure sustainable irrigation agriculture under stochastic river water quality conditions.

1. INTRODUCTION

With the projected growth in water requirements in South Africa, and assuming that current development trends and usage patterns prevail, it is estimated that the country's water resources will be fully utilised in about three decades (Basson, 1997:61). The growth in water requirements will essentially be in the domestic and industrial sectors with limited further development in irrigation and afforestation due to the foreseen shortage of water. "There are clear indications, … , that the price of water for all uses including irrigation will be adjusted upwards to better reflect the cost of supply or perhaps even its value" (Backeberg *et al*. 1996:12).

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As the use and reuse of the water resources of South Africa intensify, the general quality of supplies, both surface and ground water decline. Irrigation agriculture as a contributor to non-point-source water pollution externalities through nutrients, salts and chemicals in return flows is a global problem and one of growing concern in South Africa. Backeberg *et al*. (1996:22), states that "water quality is becoming of increasing concern to irrigation, both from a supply point of view and with respect to the environmental impacts of irrigation."

Besides increased corrosion of irrigation equipment, irrigating with water of a poor quality can have direct effects on the crop being irrigated through foliar damage or an indirect effect of salt accumulation in the soil. "The rise and fall of a number of past civilisations have been linked to their ability to sustain irrigated agriculture. The inability to control salinisation and degradation of irrigated lands are mostly viewed as main causes for their decline" (DWAF, 1993:16).

Different crops vary in their tolerance to soil and water salt concentrations. Salt concentration or salinity is measured as Total Dissolved Solids (TDS) in milligram per litre (mg/l) or Electrical Conductivity (EC) in milli-Siemens per meter (mS/m). EC is directly proportional to TDS by multiplying by a factor of between 6 and 7 depending on the composition of dissolved salts (DWAF 1993:31-35).

2. THE LEACHING PARADOX

Leaching, the process of applying water over and above the requirements of the plants irrigated, is a management practice used to "flush" a certain amount of accumulated salts out of the root zone to maintain an acceptable salt balance. This practice is often considered by non-specialists as wasteful, especially as irrigation engineers and scientists appear to be in doubt about the required leaching rates and the efficiency of the leaching practice (Kijne *et al*., 1998).

To leach effectively, soils should have a good infiltration rate till beyond the root zone. In heavy soils and where waterlogging occurs artificial drainage is required. The heavier the soils, the more expensive the costs of installing the artificial drainage. Thus the benefits of leaching need to be quantified to be able to justify the capital expenses involved.

The seepage from leaching however flows back into the river or groundwater carrying high concentrations of salts, further degrading the water source and creating secondary costs through externalities for downstream users. The paradox however is that without leaching salts, inherently found in soil or those deposited by irrigating with poor water quality, out of the soil, salts build up, degrading the soil to levels that can no longer support viable crop production. With leaching downstream water is degraded rendering it less suitable for other uses, including the environment.

3. NATURE OF THE PROBLEM

Douglas, the main town within the study area, is a thriving community in the rural Northern Cape based entirely on the forward and backward linkages of the irrigation agricultural industry. In 1984 the Orange-Vaal Irrigation Board (OVIB) was established to manage water allocations in the demarcated area. In the Vaal River system water usage is prioritised for industrial and residential use in Johannesburg, for mining purposes in the Free State gold-fields and for Vaalharts, the biggest irrigation scheme in South Africa. During times of drought in the upper Vaal River catchment, water shortages in the study area thus prevailed.

A particularly bad drought in 1992 led to the construction of the Louis Bosman Canal (completed in 1994) to transfer Orange River water to the Douglas weir. Together with the increased water security, farmers noticed a marked improvement in crop yields due to the improvement in water quality. The Department of Water Affairs and Forestry (DWAF) data shows clearly that water quality improved dramatically in the Douglas weir after Orange River water was pumped into the system.

The reason for the poor water quality was initially believed to be as a result of industry and mining in the upper reaches of the Vaal River. It has since been shown in various studies on the lower Vaal River (Du Plessis(1982), Moolman & Quibell (1995) and Nel (1995)) that the actual process of irrigation in the area displaces certain salts found inherently in the soil and releases sodium, chloride and other salts into the water while at the same time breaking down the physical structure of the soil. Although water quality does not actually worsen progressively over time within the study area, it is expected that the irrigability of soils can be affected. This, together with the current "price-cost squeeze" effect has led to the questioning of the long-term sustainability of current irrigation practices in the OVIB region.

Pumping costs, irrigation system capacity and limited drainage installation in the study area make farmers reluctant to "over irrigate" to leach out salts that have built up in the soils from years of irrigation. Because the river operates within a closed system all leachate that does occur, returns directly into the system exacerbating the water quality problem. The rapid fluctuation in water quality, especially in the Lower Riet River arm makes crop production most unpredictable, leading to instability in the region. This has resulted in a crop choice away from those with the highest returns towards bulk commodity crops with the most predictable returns under the current problem.

The price currently charged for irrigation water, is far below that paid by industry and municipal users. Farmers are also not accountable for the return flows coming off their lands. The National Water Act of 1998 however aims to address these issues and thus the need for functional models to help guide policy in the right direction, as well as to prepare farmers for the possible impacts of various scenarios.

The current research project on which this paper is based is an extension of a Water Research Commission (WRC) study titled "The Effects of Water Quality on Irrigation Farming Along the Lower Vaal River: The Influence on Soils and Crops" which has just been completed by the Department of Soil Science at the University of the Orange Free State. The aim of the current project is to build onto this study to determine the economic impact of the soil/crop yield interactions that result from changing water quality.

4. THE PROBLEM STATEMENT

Besides the expected increase in the price of irrigation water, without proactive management, water quality degradation will further jeopardise the sustainability of irrigation agriculture, and with its forward and backward linkages, the whole economy within the study area. To ensure the sustainability of irrigation farming, intensive management needs to be applied at both farm and irrigation board level to ensure water use optimisation through appropriate technology transfer and including the aim of minimising the negative effect on the environment.

The problem is thus to apply models to test the outcome of alternative scenarios regarding internal management practices and external policy measures. In pursuance of this objective, this paper presents preliminary findings of an ongoing project. Using a linear programming model all management options and possible crops are weighed up against each other to find the profit maximising combination of crops and management options under different water quality situations.

5. THE DATA

With the use of a pilot survey it was determined to what extent farmers are aware of the water quality problem and how they have adapted their management practices to the fluctuating water quality levels. The farmers are very aware of the problem and have adapted production accordingly. The farmers however indicated that they were reluctant to apply leaching practices as they have limited water quotas, and also due to the high pumping costs involved. Farmers also maintain that the capacity of their irrigation systems will not be able to apply the increased irrigation application volume needed for leaching and that leaching washes out expensive fertilisers applied to the crops. A pre-season leaching was also not an option for the farmers, as they don't have time for a heavy irrigation between harvesting and planting the next crop.

Results from the survey clearly indicate that the largest area is planted to wheat, followed by maize and then lucerne. Besides wheat, maize and lucerne certain farmers also earn a large percentage of their income from groundnuts, sunflower, potatoes, onions and vines. All, except the perennial vines, are incorporated into the current model.

Crop enterprise budgets for the area served by the Orange-Vaal Irrigation Board (OVIB) were obtained from the local extension agent at GWK (Griqualand-West Co-operative) and regional data such as total area planted, water rights allocated, etc. was obtained from the OVIB.

6. METHODOLOGY

SALMOD (Salinity and Leaching Model for Optimal irrigation Development) at its current stage of development consists of two sections; a simulation and an optimisation section.

Based on a basic variable-costs enterprise budget for each crop, the simulation section uses linear production functions to determine a range of gross margins for each crop depicting different management approaches. These gross margins are then fed into the optimisation section of the model and run to determine the profit maximising enterprise and management option combination, subject to various constraints. These constraints in turn can be adjusted to perform various "what if?" and sensitivity analyses.

7. THE LINEAR PRODUCTION FUNCTION

The maximum physiological yields (MPY's) attainable under perfect weather and management conditions for the 8 crops included in the model were determined for the study area at a technical meeting with farmers and extension officers from the study area and verified by scientists on the steering committee of the WRC project. The fraction of the MPY, Y%, that a farmer can expect to get from a specific crop, with a specific water quality and various leaching fractions, is calculated using equation 1 (adapted from Maas(1990:268) & Parker & Suarez (1990:222)):

$$Y\% = (100 - GR * (EC_e - TR) \qquad (1)$$

where:

GR is the gradient and TR the threshold value of each specific crop as determined by Francois & Maas (1994). EC_e is the electrical conductivity of the saturated soil extract. Factors as determined by Parker & Suarez (1990:222) were used to determine the relationship between irrigation water EC (EC_{iw}) and the EC_e. The gradient (GR) is the rate at which expected yield decreases as water quality deteriorates and the threshold is the maximum EC_e value up to which a crop will have no reduction in yield.

The assumption of Parker and Suarez (1990:222 & 223) is that once soils are in a state of equilibrium the relationship between EC_{iw} and EC_e remains unchanged. In the authors opinion however, this is a week assumption and a new methodology is being worked on where a complete salt balance model is incorporated into the existing model to determine this relationship more accurately. This is necessary so that the cumulative effects of salt loading on different soil types can be incorporated into a dynamic linear programming model (DLP).

8. CALCULATION OF GROSS MARGINS

Y% is multiplied by MPY to get the relative yield (Y) of a specific crop subject to a certain water quality. Y is then multiplied by the 1998 average producers price (P) to get the gross monetary returns before harvesting. As harvesting costs (HC) vary with the expected relative yield, it will be different for each leaching fraction. The increasing water and pumping costs as greater leaching fractions are used are included in the variable costs (VC) before harvesting.

The formula used to determine the Gross Margins (GM) per hectare (fixed costs excluded) is:

$$GM = (P * Y) - VC - (HC * Y) \tag{2}$$

where:

Y = Yield in ton per hectare
P = 1998 price in Rand per ton
VC = Variable costs per hectare
GM = Gross margin in Rand per hectare
HC = Harvesting costs per ton

This gross margin is used in the objective function row of the optimisation section of the model to determine the most profitable combination of enterprise composition and management practices subject to various constraints

The linear programming (LP) model

The objective function of the LP model is to maximise profit (π). GM_{ilmn} denotes the gross margin coefficients in the objective function, and is a set of constants as determined in the simulation section of the model. The choice variables denoted by X_{ilmn} are: area planted to different possible crops, using different irrigation frequencies, on different soil types and each with a range of leaching fractions, i.e.:

i = the number of enterprise options to be included (c = 8 in this model)
l = the number of specific leaching fractions to be include in the model (f = 5; no leaching on unleachable soils, and on leachable soils, 0, 5, 10 & 15% leaching fractions)
m = the soil type (g = 2; in this model a distinction is only made between sandy and clay soils)
n = the watering frequency of the irrigation system (r = 2; high and low frequency irrigation)

This results in 8x5x2x2 = 160 possible crop and management activity combinations to consider with the objective of profit maximisation and certain constraints.

The constraints incorporated into this model are of three basic types, land constraints, constraints ensuring good agronomic practice and crop water use constraints. The crop water use constraints are reflected in the stepwise fines (F) charged for exceeding the water quota. The fine for irrigating more than the allocated quota in the aft-season (December to June) is charged in increments of 1000mm at a rate of 1.5, 2, 2.5 & 3 times that of the normal cost of water (R0.17 per mm). A flat rate of R1.00 per mm overuse is charged in the dry pre-season (July to December). There is thus s = 1 to t (t=5) levels of fines associated with F in the objective function. There is also a fixed cost component to denote annual fixed costs (K) that will vary for each individual farmer.

This LP maximisation problem written in algebraic notation is thus:

Objective function

$$MAX = \sum_{ilmn} GM_{ilmn} * X_{ilmn} - \sum_{s} F_s * W_s - K \qquad \begin{matrix} (i = 1, 2, \dots, c) \\ (l = 1, 2, \dots, f) \\ (m = 1, 2, \dots, g) \\ (n = 1, 2, \dots, r) \\ (s = 1, 2, \dots, t) \end{matrix}$$

Subject to constraints:

$$\sum_{ilmn} a_{ilmnj} * X_{ilmn} \pm \sum_{s} b_{sj} * W_s \quad \leq, \geq or = R_j \qquad (j = 1, 2, \dots, z)$$

and $$X_{ilmn}, \quad W_s \quad \geq 0 \qquad (3)$$

where:

- ***a*** and ***b*** denote the various coefficients of the *X* and ***W*** variables respectively
- $\boldsymbol{X_{ilmn}}$ denotes hectares planted to various crop and management options and
- $\boldsymbol{W_s}$ denotes mm water usage over and above the allocated quota at increasing block tariff rates.

THE RESULTS

For the purpose of this paper, the model is run at farm level. A case study farmer who possesses 200 ha's of land, of which 90% are leachable and who only has 141 hectares of water rights, is used. This is quite typical of the study area. For the case study farm, the optimal enterprise composition is determined. The resulting optimal irrigation gross margins as water quality deteriorates are displayed in Figure 1 below.

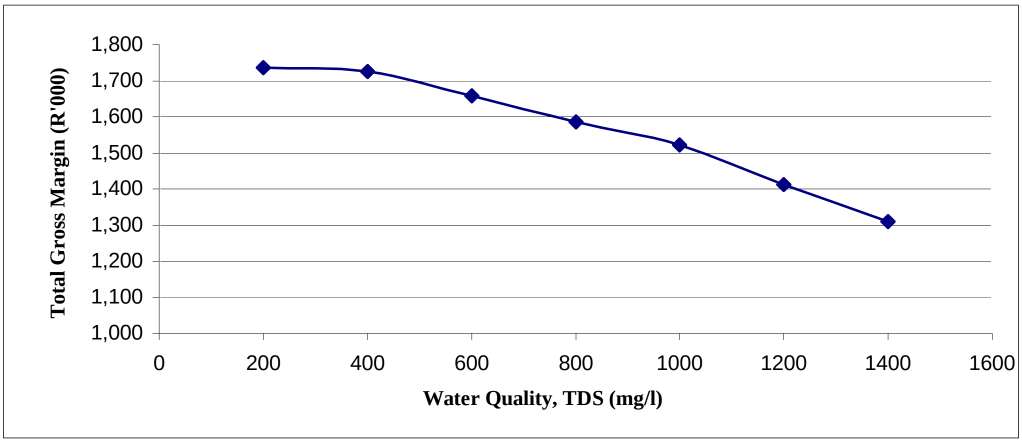

Figure 1: Reduction in optimal Total Gross Margin as water quality deteriorates

Results also partially confirm the initial hypothesis that under conditions of irrigation water salinity farmers will move away from crops with larger returns (e.g. potatoes, onions and groundnuts) to the crops with constant yields under saline conditions (e.g. wheat & cotton). In Table 1 optimal enterprise composition stays relatively unchanged until water quality exceeds 800 mg TDS/l. At this point onions are no longer planted and are replaced by cotton. Potatoes however, being the highest value crop are planted to maximum levels as water quality decreases, utilising increasingly higher leaching requirements. Wheat and maize area is reduced as salinity increases to be replaced by cotton. However, note that the case study farm consists of 90% leachable soils – the results in table 1 are very different when the model is constructed as if leaching is not practised, or soils are unleachable.

SUMMARY AND RECOMMENDATIONS

In this paper a linear programming model is used at farm level to determine the optimal enterprise composition for irrigation farming subject to irrigation water salinity.

This paper outlines the methodology followed in developing a farm level and irrigation scheme level economic management model for the Orange-Vaal Irrigation Board (OVIB). Distinguishing between soil types and irrigation method used, SALMOD determines the optimal levels to leach the crops that have been included in the objective function maximising enterprise combination so as to ensure optimal farm profits.

Table 1: Optimal enterprise composition at different water qualities

Water Quality (TDS in mg/l)	*Current*	*SALMOD optimal enterprise composition (ha)*						
	600	200	400	600	800	1000	1200	1400
RETURNS (R'000)	***966***	**1736**	**1725**	**1658**	**1585**	**1522**	**1413**	**1310**
Wheat	*120*	71	70	78	82	76	63	63
Maize	*96*	140	140	128	112	101	77	74
Potato	*10*	20	20	32	40	40	40	40
Onion	*0*	20	20	8	0	0	0	0
Cotton	*0*	0	0	0	8	19	43	46
Sunflower	*0*	0	0	0	0	0	0	0
Groundnut	*15*	0	0	0	0	0	0	0
Lucerne	*20*	40	40	40	40	40	40	40
Total ha's planted	***261***	**291**	**290**	**287**	**282**	**276**	**263**	**263**
Returnflows (mm)	*0*	0	880	7182	11785	13760	18077	18125

Particularly useful data generated by SALMOD for use in environmental and social impact assessment is the volume of salt loaded return-flows that either leach into groundwater aquifers or are returned into the river system as a "diffuse pollution source". The model gives a good indication of a farmer's specific contribution to the diffuse or non-point source pollution problem. The economic effects of constraining return-flow and the effects of water pricing policy on the volume of return flows can also be determined. Irrigation waters of different qualities are essentially different commodities for which different rates should be charged.

Currently the water quota allocation system is based on a per hectare basis and not on a volumetric basis. This totally distorts incentives for efficiency in irrigation water application and while indirectly stimulating leaching, can contribute to large environmental externalities.

The results clearly indicate that improved returns can be generated from effective leaching and optimising enterprise composition for an expected water quality. Under the water quality levels that currently prevail in the study area, optimal enterprise composition remains fairly unchanged. However, exceeding a water quality of 800mg TDS/l, cotton totally replaces onions, and due to the higher leaching requirements of potatoes, maize and wheat to an extent as well in the optimal enterprise composition.

As long as the current water-pricing system prevails, greater returns from leaching more than compensate for the pumping costs involved. Irrigation agriculture however has to be managed diligently to ensure its long-term sustainability, and with the expected increases in the price of water it is going to be imperative to implement appropriate management systems at both farmer and board level. The irrigation board could thus generate greater returns by charging for actual water used, and not area planted. This will result in increased returns which can then be used to pump Orange River water into the study area to, through dilution, guarantee a better water quality which will improve the sustainability of irrigation farming in the region. In this way return flows can also be monitored and managed.

The trade-off that still needs to be quantified is between leaching, which is essential to maintain the socio-economic sustainability of irrigation agriculture and the downstream effects on environmental sustainability resulting from increased leaching. Without leaching, current irrigated areas will develop into an ecological wasteland, and through leaching the downstream ecological balance can be disturbed and other irrigation areas impacted on through increased irrigation water salinity.

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