
EXECUTIVE SUMMARY

GENERALISED WHOLE-FARM STOCHASTIC DYNAMIC PROGRAMMING MODEL TO OPTIMISE AGRICULTURAL WATER USE

Motivation

The National Water Resources Strategy (NWRS) (DWAF, 2004) is a requirement of the National Water Act (Act 36 of 1998) and describes how the water of South Africa will be protected, used, developed, conserved and managed. The NWRS seeks to identify opportunities where water can be made available for productive livelihoods and also to give the support and assistance needed to use the water effectively. The National Water Conservation and Demand Management Strategy forms an integral part of the NWRS. The agricultural sectoral strategy was recently finalised and endeavours to provide a supportive and enabling framework to improve irrigation efficiency. Thus, there is a clear need to optimise water use in the agricultural sector. Strategies to increase efficiency of water use are both of short and long term nature.

A decade ago Backeberg and Oosthuizen (1995) posed the challenge to researchers to develop and apply dynamic stochastic planning methods for managing water resource allocation problems. When dealing with the allocation of water resources between competing uses, optimisation techniques are preferred because they take the opportunity cost of water into account and are able to predict how farmers are to respond to certain changes in water policy. Researchers in South Africa seem to favour dynamic linear programming (DLP) to optimise water resources allocation problems and the economic implications of alternative water policies (Van Schalkwyk and Louw, 2004; Louw, Van Schalkwyk and Groenewald 1998; Backeberg, 1997; Viljoen, Symington and Botha, 1992; Mare, 1995 and Haile, Grové and Oosthuizen, 2003).

Oosthuizen and Grové (2000) demonstrated, through the development of linear and non-linear optimisation models of agricultural water use management at farm level, that the timing of water shortages significantly impacted on the economic efficiency of irrigation farming. They also demonstrated that the combined effect of water shortages in different crop growth stages significantly alter optimal water use patterns over the growing season and thus economic efficiency. Early research efforts to optimise agricultural water use within a DLP framework focused on the use of production functions to estimate alternative activities for their programming models, i.e. Viljoen, Symington, Botha and Du Plessis (1993). Production functions aim at optimising seasonal water use and are not suited for situations where different crops compete for water within a season or where water supply limitations occur for a fraction of

the season (Bernardo, 1985). Thus, the ability to optimise agricultural water use between multiple crops within a DLP framework still needs to be demonstrated. Another complicating factor is that water is classified as a risk reducing input, and by implication lower water application levels will therefore increase production risk (Willis, 1993). Due to a general lack of understanding of available procedures and models to adequately describe and quantify the risks associated with key decision variables, no attempt was previously made in South Africa to incorporate production risk into DLP models with the aim of optimising agricultural water use.

Problem statement and formulation of objectives

The necessity to apply stochastic dynamic planning methods to evaluate alternative water allocation policies and water use strategies has become more acute in the presence of increased risk faced by farmers as well as increasing scarcity of water supplies. The lack of a generalised model that is able to optimise agricultural water use between multiple crops while taking into account the dynamic and stochastic environment within which decisions are made, hamper the development of appropriate optimal water use plans in the agricultural sector.

The main objective of this research was to develop a generalised whole-farm stochastic dynamic linear programming model to assist water user associations (WUA) with optimal water use within the framework of integrated catchment management.

Specific objectives were:

1. To develop a generalised whole-farm dynamic linear programming (DLP) with the emphasis on optimising water use between multiple crops taking the timing of water limitations on crop yield into account.
2. To quantify long run production risk and to develop procedures to incorporate these risks into the DLP model.
3. To optimise water use for an irrigation scheme through the linking of the individual representative DLP models.

Methodology

The research was done in Vaalharts, the largest irrigation scheme in South Africa which comprises a total of 37 000 hectares of land, farmed by some 680 landowners. Canals supply the water to the irrigation plots. The two main canals, the northern canal and the western canal, feed a network of feeder and community canals. The water quota for the north and west canal is 9 140 m³ per ha, resulting in an annual water use right of 209 744 720 m³ for the north canal and 57 143 280 m³ for the west canal (Van Heerden, 2001). Flood irrigation is the dominant irrigation type followed by pivot irrigation. The most important cash crops in the valley are maize, groundnuts, wheat, lucerne and cotton and the most important long-term crop is pecan nuts.

GAMS (General Algebraic Modelling System) was chosen as the preferred modelling environment to develop the generalised stochastic DLP model since it allows for the construction of the programming matrix through the use of generalised mathematical equations. Furthermore it is the standard in optimisation software used by agricultural economists locally and internationally.

Principles that guided the development of the skeleton model were that of generality and minimum inputs. Thus, the model was developed in such a way that alternative farming situations that differ in terms of irrigation distribution network and current use of resources by irrigation systems and long-term crops can be modelled without changing the structure of the model. On the contrary, the inputs determine the structure of the model. On the other hand, minimum inputs imply that if it is less data-intensive to calculate specific input parameters from specified inputs, the user will not be asked to supply the more data-intensive parameters but rather these parameters will be calculated.

With the above-mentioned guiding principles a deterministic version of the model which focused on the financial feasibility of irrigation system investments was developed first. This was a necessary step to develop the accounting equations that link the cash flows dynamically from year one to the end of the planning horizon while taking the time value of money into account. Special care was taken during the development of the deterministic model to ensure that all relevant cash income and expenses were accounted for according to standard capital budgeting procedures. A unique feature of the model is that it has the ability to defer tax payments to later years if the tax deductions are more than the annual income. The normative approach proposed by Rae (1970) was used to account for any cash flow streams beyond the planning horizon. With the normative approach a terminal value is calculated for each activity as the present value of future net revenue discounted from infinity for an assumed replacement cycle which may exceed the planning horizon based on the timing of the investment. Terminal values ensure that capital investments with cash flow streams beyond the planning horizon are not penalised while investments and cash generating cropping activities are optimised.

The next step was to develop procedures to optimise water use between multiple crops that compete for water during more than one time period under limited water supply conditions. These conditions require the optimisation of a soil water budget continuum which relates the impacts of irrigation decisions made in a specific period to those in next periods through changes in the soil water budget. Procedures developed by Bernardo (1985) were used to approximate the exact solution to the problem. With this procedure possible irrigation amounts with a discrete interval from zero to full irrigation are decided on for each period in accordance with application rates within typical irrigation cycles. After these amounts were quantified the impact on water use and final crop yield was simulated with a crop growth simulation model for all possible irrigation application combinations. Each irrigation application combination for each crop was included in the DLP model as an alternative irrigation regime over the growing season

of the crop. The DLP model was then used to determine the optimal regime for each crop within the constraints of the whole farm. Excel® macros were used to simulate the impact of these alternative irrigation application combinations for each crop with a modified Excel® version of SAPWAT. Modifications to the existing SAPWAT included the calculation of crop yields with relative evapotranspiration formulae and procedures to adjust irrigation efficiency as the crop is deficit irrigated. Procedures developed by Li (1998) which take the uniformity of irrigation applications of a specific irrigation system into account were used to change irrigation efficiency as the crop is deficit irrigated. Since the procedures to optimise water use between multiple crops hinge on the crop growth simulation, the simulation model can also be used to quantify production risk.

The last step in developing the stochastic DLP model was to develop procedures to incorporate risk into the model. Risk was incorporated into the DLP model via a mean variance framework. More specifically the procedures of Bussey (1978) were used to discount the variance of the farm plan to present values while taking the temporal and intertemporal correlation between stochastic variables into account. The variance-covariance matrix was constructed using simulation procedures developed by Richardson, Klose and Gray (2000). The last mentioned procedures can also be used to simulate appropriately correlated entities over the long term for application with the MOTAD procedure which is the linear approximation of the quadratic programming model.

To demonstrate the applicability of the model it was applied to the Vaalharts irrigation scheme.

Results and conclusions

Overall the results of the model indicated that it reacts as expected when motivated with the expansion of pivot irrigation.

- Results of the water reallocation tradeoffs indicated that the tradeoffs between alternative scenarios differ significantly. In general the results indicated that if it is feasible to include pecan nuts, the expected net present value will be higher. However, the impact of water shortages will be more severe. Furthermore farmers with cash crops will have the highest manoeuvrability to cope with water reallocation through the adoption of more efficient centre pivot irrigation. The conclusion is that farmers with high value crops such as pecan nuts will need a higher security of supply compared to cash crop farming. Furthermore it is concluded that the DLP model was able to correctly identify changes in the slope of the tradeoff curve which indicates that the model behaves as expected.
- When risk is taken into account results showed that little tradeoff exists at the total canal level since the farmers specialised in lucerne for which risk was not taken into account. However, at the farm level positive and negative tradeoffs were modelled. These tradeoffs are modelled due to the single decision-maker framework and because

several farmers use one canal. Thus, if canal capacity is limiting, the model will allocate water to those farms with higher marginal values. The conclusion is that it is imperative to develop procedures to handle risk for the long-term crops.

- Although risk plays an important role in the optimal development path of a farm, the timing of water shortages did not impact severely on the risk return tradeoffs. However, it does seem as if the time value of money plays an important role in the calculation of forgone income due to water shortages.

Achievement of set objectives and value of the model

The main objective of this research was achieved through the development and application of a whole-farm stochastic DLP model to assist the WUA in Vaalharts with optimal water use at the farm and WUA level.

More specifically the following objectives were achieved:

- Procedures were developed to separate data manipulation and calculation of input parameters from the matrix generating equations used to construct the model. Through the adoption of such a procedure the accounting equations that determine the underlying structure of the programming matrix is more transparent. Thus, it will be easy for new researchers to understand the underlying structure of the DLP model and to modify the equations for highly specialised applications.
- The GAMS code is structured in such a way that the input parameters determine the structure of the programming model and the extent (farm versus combination of farms) of the analysis. People without any programming experience will thus be able to analyse alternative farming situations through changes in the inputs parameters without having to change any of the mathematical equations that define the optimisation model. It is thus possible to give tailored advice to a specific farmer.
- The normative approach used to calculate terminal values from long-term enterprise budgets and capital budgets based on the economic life of investments overcomes the difficulty of specifying terminal values. Parameter inputs are thus reduced and allow for any planning horizon to be analysed without specifying additional inputs.
- The DLP model is theoretically sound and is based on standard capital budgeting procedures. All the necessary cash inflows and outflows are dynamically accounted for and the model is therefore able to model cashflows better when compared to any of the other DLP models in South Africa. More specifically the ability of the model to defer tax payments to later years is unique. Thus, the model is able to evaluate the cash flow implications of alternative investment decisions more accurately, thereby enhancing the quality of advice that farmers can get.
- Procedures were developed to empower the user of the model to optimise agricultural water use between multiple crops that compete for water during more than one time period under limited water supply conditions within a whole-farm or a group of farms

along a canal section within a WUA. For the first time in history, agricultural advisors will be able to comprehensively assess the water use of irrigation farmers while taking interdependent farm level constraints into account.

- The capacity of SAPWAT to evaluate alternative irrigation schedules under limited water supply conditions was extended through the development of procedures to alter irrigation efficiency based on the irrigation systems' uniformity and the calculation of crop yields.
- Stand-alone GAMS code was developed to simulate appropriately correlated sequences of gross margins. These procedures can be used by other researchers to incorporate risk into their models.
- The DLP model integrates the water distribution network managed by the WUA and water use at the whole-farm level which is managed by the irrigation farmer. The DLP model will therefore be able to help in the development of credible water management plans from a WUA and farmer perspective.

Research and technology transfer proposals

- The potential of the skeleton model to evaluate alternative water reallocation problems and to be used as a tool to give extension advice can only be unlocked through appropriate technology transfer actions. The train-the-advisor concept will add to the number of people who may benefit from developing the skeleton model. Potential clients include researchers, agricultural advisors, water managers and extension officers from the National Department of Agriculture.
- Research is also necessary to formalise the links between different models that can provide the information for the skeleton model within a GIS environment such as SWB and WAS.
- Although the skeleton model takes production risk into account, procedures need to be developed to include the impact of stochastic water supply conditions on irrigation farming profitability and development over time.
- The procedures used to include production risk into the model assume that risk is additive. A more robust procedure is necessary to model risk as multiplicative. The use of expected utility maximisation of non-parametric distributions needs to be investigated.