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

B Grové

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

by B. GROVÉ

Report to the Water Research Commission

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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 m^3 per ha, resulting in an annual water use right of 209 744 720 m^3 for the north canal and 57 143 280 m^3 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 where 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.

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INTRODUCTION

1.1 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.

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1.2 PROBLEM STATEMENT

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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.

The envisaged model and procedures will allow water policy makers for the first time to evaluate alternative water allocation policies through the linking of individual representative farm models. Furthermore the detail included in the farm-level models will allow farmers to evaluate specific water conservation strategies on their long-term profitability taking risk into account.

1.3 METHODS

The General Algebraic Modelling System (Brooke, Kendrick, Meeraus and Raman, 1998) is used to develop the generalised structure of the skeleton DLP model. Special care was taken to develop the equations used to represent the programming matrix in such a way that the input parameters will determine the final structure of the model. Thus, different water supply and resource use situations can be modelled with the same model, but different input parameters. A normative approach is used to calculate the terminal values from input parameters and therefore it is not necessary to explicitly input terminal values. The model uses constant prices and allows for any time frame to be optimised. No data manipulation takes place when the matrix is generated and GAMS code was developed to calculate all the input parameters before they enter the programming model. Through this procedure it is easier to verify that the input parameters are calculated correctly.

Methodologies developed by Bernardo (1985) are used to optimise water use between multiple crops. To apply his methodology one needs to develop a series of technical efficient and inefficient irrigation schedules for alternative crops which are used as the cropping activities within a linear programming model. Given the availability of a crop growth simulation model the production risk associated with each of these activities can be simulated. SAPWAT (Van Heerden, Crosby and Crosby, 2001) was used to estimate the crop water requirements of the alternative irrigation schedules. Gross irrigation requirements for a specific irrigation schedule were calculated using the uniformity of the irrigation system (Li, 1998). Output from SAPWAT was linked to a relative evapotranspiration crop yield model (De Jager, 1994) to estimate the crop yield variability associated with each irrigation schedule.

Risk can be incorporated into the model using quadratic risk programming or its linear alternative MOTAD. When incorporating risk into a DLP programming model a problem often encountered is the specification of the intertemporal variance-covariance matrix or when using MOTAD appropriately specified sequences of gross margins to calculate deviations. To facilitate stochastic input parameter specification, a separate risk simulation model was coded in GAMS to generate the necessary risk input parameters. For this purpose procedures developed by Richardson, Schumann and Feldman (2004) are used.

The model is applied to the Vaalharts water user association to model the tradeoffs of alternative water supply and irrigation demand scenarios.

1.4 REPORT STRUCTURE

The content of this report consists of five chapters as well as an executive summary and research implications.

Chapter 2 gives an overview of the theoretical foundations of water use optimisation between multiple crops under conditions of limited water supply. The latter part of the chapter is used to review mathematical programming applications and ways to incorporate risk into DLP models.

A short description of Vaalharts, its water resources and management of the resources is given in Chapter 3.

The majority of Chapter 4 is used to describe the DLP skeleton model and the procedures used to generate the input parameters. The second part of the chapter is devoted to the application of the model in Vaalharts and the procedures used to generate the necessary risk input parameters.

Chapter 5 presents the model results, discussion and conclusions.

The implications for further research are shown at the end of the report.

The data and models used in this report are archived in the Department of Agricultural Economics, University of the Free State, Bloemfontein, LG 1.106.

CHAPTER 2

LITERATURE REVIEW

The main objective of the literature review is to review economic theory of water allocation and to evaluate the use of dynamic linear programming models to optimise crop water use between multiple crops.

2.1 ECONOMIC THEORY OF WATER USE OPTIMISATION AND ITS APPLICATION

Understanding the relationship between applied water and consumptively used water by the crop is critical in achieving optimal water use[1] allocation. In order to optimise agricultural water use one needs to relate applied water to some measure of crop water consumption since consumptively used water is directly related to crop yield. Evapotranspiration (ET) is preferred by many researchers as a measure of crop consumptive water use although it does include evaporation from the soil. The reason is that a considerable number of researchers found a linear relationship between ET and crop yield (Vaux and Pruitt, 1983; Stewart and Hagan, 1973). Figure 2.1 is used to explain the relationship between field water supply and ET. Field water supply consists of irrigation water stored in the root zone, effective rainfall and soil water carry-over.

From Figure 2.1 it is clear that some crop yield (Y_o) is possible without applying any water. Y_o corresponds to dryland crop yield and Y_m to maximum crop yield under irrigation. A linear relationship between crop yield and ET is shown. However, the relationship between applied water and crop yield is non-linear. The horizontal difference between ET and applied water constitutes irrigation losses such as deep percolation and runoff after wind drift are taken into account. The amount of losses increases if you irrigate to achieve maximum crop yield. The reason is that if applied water is well below the level needed for maximum yield, deep percolation and runoff are minimised since the soil profile is left drier.

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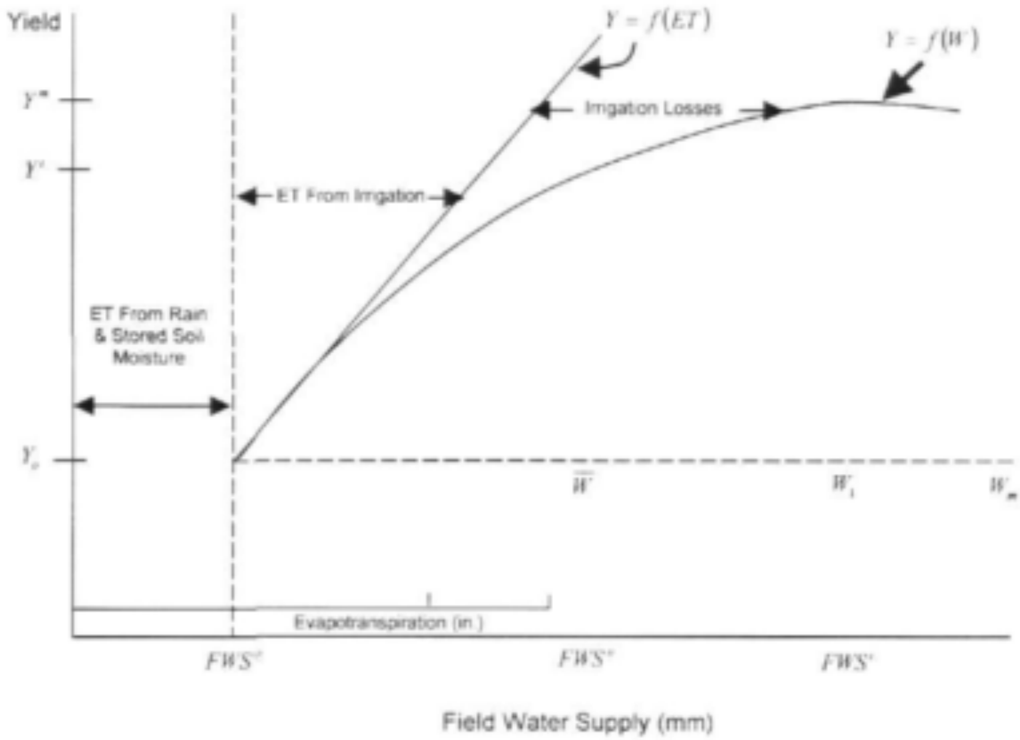
[1] Crop water use refers to the gross amount of water used to produce a specific crop with a given technology and management regime while consumptively used water relates to the amount of water actually consumed by the crop.



Source: Bernardo (1985)

Figure 2.1: Relationship between crop yield evapotranspiration and applied water.

The impact of an irrigation system on water losses and crop yield can be incorporated using the uniformity with which an irrigation system applies water (De Juan, Tarjuelo, Valiente and Garcia, 1996; Mantovani, Villalobos, Orgaz and Fereres, 1995).

Once these relationships are quantified, economic theory should guide the optimal allocation of water. Next sections draw heavily on the work by Bernardo (1985) to establish a theoretical framework for allocating water under single-period, multiperiod and multiple crop conditions.

2.1.1 SINGLE PERIOD

Assuming energy and labour requirements may be specified as a function of water use (W), the profit function may be specified as

$$2.1 \qquad \Pi = P_y \cdot f(x_1, \ldots, x_n, w) - A - \sum_{i=1}^{n} r_i x_i - r_w w - r_e \cdot E(w) - r_\lambda \cdot L(w)$$

In this specification, E and L are expressions relating energy and labour use to the seasonal irrigation depth and r_e, r_λ, and r_w are the prices of energy, labour, and water, respectively. Under this scenario, the first-order conditions for profit maximization are:

2.2 $$P_y \cdot f_i - r_i = 0 \qquad (i = 1, \ldots, n)$$
$$P_y \cdot f_w - r_w - r_e \cdot \partial L/\partial w = 0$$

When land is the limiting input, the objective is to maximise profit per unit land area. The optimal seasonal irrigation depth is the water application required to equate the marginal value product of water with the marginal factor cost of applying a unit of water (including the energy and labour requirements). Mathematically this condition is given by:

2.3 $$P_y \cdot f_w = r_w + r_e \cdot \partial E/\partial w + r_\lambda \cdot \partial L/\partial w$$

The optimisation problem when annual water availability is limited to the quantity $(\overline{W})$ becomes

2.4 Max $$\Pi = P_y \cdot f(x_1, \ldots, x_n, w) - A - \sum_{i=1}^{n} r_i x_i - r_w w - r_e \cdot E(w) - r_\lambda \cdot L(w)$$
s.t. $$w \leq \overline{W}$$

The Lagrangian function defined by the constrained optimisation problem is

2.5 $$T = P_y \cdot f(x_1, \ldots, x_n, w) - A - \sum_{i=1}^{n} r_i x_i - r_w w - r_e \cdot E(w) - r_\lambda \cdot L(w) + \lambda(\overline{W} - w)$$

The resulting first-order conditions, assuming the available water supply is totally exhausted are:

2.6 $$P_y \cdot f_i - r_i = 0 \qquad (i = 1, \ldots, n)$$
$$P_y \cdot f_w - r_w - \partial E/\partial w \cdot r_e - \partial L/\partial w \cdot r_\lambda - \lambda = 0$$
$$\overline{W} - w = 0$$

In this case, the optimal irrigation depth is the quantity which results in the equality

2.7 $$P_y \cdot f_w = r_w + \partial E/\partial w \cdot r_e - \partial L/\partial w \cdot r_\lambda + \lambda$$

The Lagrangian multiplier (λ) represents the marginal value product (MVP) of water in the production of the output y. Instituting a water supply restriction results in a further decrease in the optimal annual irrigation depth. The marginal value product of water is equated to the sum of the marginal factor cost of applying a unit of water (the market price of water + energy + labour) and its scarcity value.

2.1.2 MULTIPERIOD

To illustrate the influence of time considerations on the optimality conditions, a relatively simple example of time-dependent response is considered below. This example will serve to illustrate the interdependency of the sequential decisions defining an optimal intraseasonal water allocation.

To evaluate the effect of time on irrigator decision-making, consider the case of allocating a finite water supply to a single crop. For simplicity, it is assumed the irrigation season comprises of n discrete subperiods. The management objective may be defined mathematically using the following separable objective function:

2.8 $$Max\sum_{i=1}^{n} NR_i(WA_i, I_i)$$

where: NR_i = net returns from stage i

WA_i = the state vector describing the soil moisture status in period i

I_i = the quantity of water applied in period i

In the usual reverse order of dynamic programming, i is used to denote that period after which $i-1$ further runs of the response process are made.

The irrigator seeks to maximise returns over the n periods by choosing irrigation quantities in each of the n periods $(I_1, I_2, ..., I_n)$. If an irrigation is to be applied, it is assumed to occur at the beginning of each subperiod. Thus, the soil-moisture status in period i (WA_i) is defined by the soil moisture carried over into period i (R_i) and the depth of irrigation in the period (I_i). Therefore, a response function relating yield to soil-moisture status in period i may be defined as

2.9 $$f_i[WA_i(R_i, I_i)]$$

Note that yield is a function of the state of the soil-plant system rather than the total physical quantity of input applied in the season. The function f_i is assumed to exhibit diminishing returns so that the required second-order conditions for optimality hold. In addition, the specification of f_t differs among periods, accounting for the changing marginal productivity of water use over time.

The optimisation problem includes a transformation function (a recursion relation) that describes the transition of soil-moisture status from the initial stage to the final stage. This expression may be written as:

2.10 $$R_i = V_i\left(I_{i+1}, R_{i+1}\right)$$

As in the timeless case presented in Section 3.2, the problem is subject to the proviso that the total amount of water applied must be less than the total available water *(W)*. That is:

2.11 $$\sum_{i=1}^{n} I_i \leq \overline{W}$$

Abstracting from any uncertainties in price or yield, recurrence equations of the usual dynamic programming form may be formulated. Net returns are determined by subtracting variable costs from total revenue. For the case with only one period remaining (i.e., $n = 1$), the objective function may be defined as:

2.12 $$\max T_1\left(WA_1\right) = P_y \cdot f_1\left[WA_1\left(R_1, I_1\right)\right] - r_w I_1 - r_e \cdot E_1\left(I_1\right) - r_\lambda \cdot L_1\left(I_1\right) + \lambda_1\left(\sum_{i=1}^{n} I_i - \overline{W}\right)$$

Differentiating the expression with respect to the decision variable I_1, yields the final-period condition for profit maximisation:

2.13 $$P_y \cdot \partial f_1 / \partial WA_1 \cdot \partial WA_1 / \partial WA_1 = r_w + r_e \cdot \partial E_1 / \partial I_1 \cdot r_\lambda \cdot \partial L_1 / \partial I_1 + \lambda_1$$

Water is applied to the level required to equate the MVP of water applied in period one to its marginal factor cost. Continuing for the case with two periods remaining, the objective function becomes:

2.14 $$T_2\left(WA_2\right) = P_y \cdot f_2\left[WA_2\left(R_2 I_2\right)\right] - r_w I_2 \cdot r_e \cdot E_2\left(I_2\right) - r_L \cdot L_2\left(I_2\right) - \lambda_2\left[\sum_{i=2}^{n} I_n - \left(\overline{W} - I_1\right)\right] + \begin{Bmatrix} P_y \cdot f_1 - \left\{WA_1\left[R_1\left(R_2, I_2\right), I_1^*\right]\right\} - r_w I_1^* \\ - r_e \cdot E_1\left(I_1\right) - r_\lambda \cdot L_1\left(I_1\right) \end{Bmatrix}$$

The resulting second-period condition for optimality is:

2.15 $$P_y\left(\partial f_2/\partial WA_2 \cdot \partial WA_2/\partial I_2 + \partial f_1/\partial WA_1 \cdot \partial WA_1/\partial R_1 \cdot \partial R_1/\partial I_2\right) = r_w + r_e \cdot \partial E_2/\partial I_2 + r_\lambda \cdot \partial L_2/\partial I_2 + \lambda_2$$

Equation 2.15 illustrates the interdependence of the sequential irrigation decisions. This expression states that the sum of marginal value product of a unit of water applied in period two and the impact on period one revenues resulting from applying a unit of water in period two must equal the marginal factor cost of applying a unit of water in the second period. The interaction between the two periods is a consequence of the value of the additional soil moisture from I_2 carried over to period one.

2.1.3 MULTIPLE CROPS

To illustrate the influence of time on the optimality conditions for intercrop water allocation, the irrigation season is divided into three discrete subperiods. Two independent response processes are assumed and expressed as:

2.16 $$Y_h = f_h\left(w_{1h}, w_{2h}, w_{3h}, x_h\right) \qquad (h = 1, 2)$$

where: w_{ih} = water applied to the h-th crop in period i

x_h = the quantity of a composite input x applied crop h

The problem faced by a profit-maximizing producer seeking to allocate a finite seasonal water allotment $\left(\overline{W}\right)$ over the three periods may be represented as:

2.17 $$\max \quad P_1 \cdot f_1\left(w_{11}, w_{21}, w_{31}, x_1\right) + P_2 \cdot f_2\left(w_{12}, w_{22}, w_{32}, x_2\right) - r_w\left(\sum_{h=1}^{2}\sum_{i=1}^{3} w_{ih}\right) - r_x\left(x_1 + x_2\right)$$

$$\text{s.t.} \quad \sum_{h=1}^{2}\sum_{i=1}^{3} w_{ih} \leq \overline{W}$$

where: P_h = the price of product h

r_x = the price of composite input x

Assuming the water supply is totally exhausted, optimal irrigation sequencing and intercrop water allocation must satisfy the following conditions:[2]

2.18 $$P_h \cdot \partial f_h / \partial w_{ih} = r_w + \lambda \qquad (h = 1, 2;\ i = 1, 2, 3)$$

$$P_h \cdot \partial f_h / \partial w_h = r_z \qquad (h = 1, 2)$$

$$\sum_{h=1}^{2} \sum_{i=1}^{3} w_{ih} = \overline{W}$$

The optimal intraseasonal water allocation requires that the marginal value product of water between crops and among the three subperiods be equivalent. In this case the necessary conditions for optimality require that the marginal value products of water equal the sum of the price of water and its shadow price.

When a limitation is placed on the seasonal water allotment, the optimal irrigation schedules will result in the maximum yields attainable from the seasonal irrigation depths allocated to each crop. That is, the assumption of technical efficiency is met, and the optimal schedule may be represented as a point on the upper envelope curve shown in Figure 2.2. This curve represents the locus of points of maximum water-use efficiency for each level op seasonal irrigation depth. Technically efficient points must be characterised by the condition that the marginal product of water for a particular crop must be equivalent across subperiods. That is, no reallocation of water between subperiods may increase yield. The condition is met in the above first-order conditions, where the marginal product of water used in each subperiod is equivalent to the constant $[(r_w + \lambda) / P_h]$.

When restrictions are imposed on the intraseasonal distribution of water, optimal irrigation activities need not be technically efficient. Distributional considerations may dictate the selection of activities represented by points below the envelope of technically efficient irrigation activities. To analyse the effect of restrictions on the temporal distribution of water use, a constraint on the quantity of water available in period three (W_3) is added to the formulation presented in equation 2.17.

[2] λ is the Lagrangian multiplier on the annual water constraint and represents the shadow price of water.

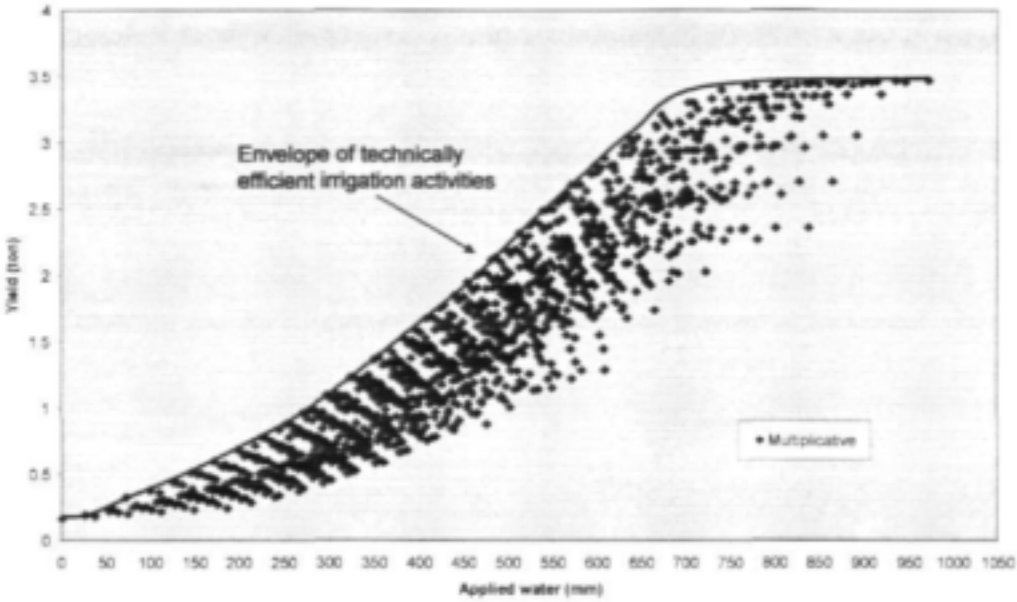


Figure 2.2: Envelope of technically efficient irrigation activities.

The optimisation problem becomes:

2.19

$$\max \quad P_1 \cdot f_1(w_{11}, w_{21}, w_{31}, x_1) + P_2 \cdot f_2(w_{12}, w_{22}, w_{32}, x_2) - r_w\left(\sum_{h=1}^{2}\sum_{i=1}^{3} w_{ih}\right) - r_x(x_1 + x_2)$$

$$\text{s.t.} \quad \sum_{h=1}^{2}\sum_{i=1}^{3} w_{ih} \le \overline{W}$$

$$w_{31} + w_{32} \le \overline{W_3}$$

The resulting first-order conditions are:

2.20

$$P_h \cdot \partial f_i / \partial w_{ih} = r_w + \lambda_1 \qquad (h = 1, 2;\ i = 1, 2)$$

$$P_h \cdot \partial f_h / \partial w_{3h} = r_x + \lambda_1 + \lambda_2 \qquad (h = 1, 2)$$

$$P_h \cdot \partial f_h / \partial x_h = r_x \qquad (h = 1, 2)$$

$$\sum_{h=1}^{2}\sum_{i=1}^{3} w_{ih} = \overline{W}$$

$$w_{31} + w_{32} \le \overline{W_3}$$

λ_1 and λ_2 represent the Lagrangian multipliers on the annual and third-period water supply constraints. For water applied in periods one and two these conditions are equivalent to those in Equation 2.18. Optimality conditions for period three water also require that the MVP of water equals the price of water plus its shadow price. In this case, however, the shadow price has an added scarcity value dictated by the constraint on period-three water use.

These conditions can be used to illustrate that economically efficient irrigation schedules need not be technically efficient. Algebraic manipulation of the first-order conditions gives

2.21
$$\partial f_1/\partial w_{11} = [(r_w + \lambda_1)/P_1]$$
$$\partial f_1/\partial w_{21} = [(r_w + \lambda_1)/P_1]$$
$$\partial f_1/\partial w_{31} = [(r_w + \lambda_1 + \lambda_2)/P_1]$$

Therefore, the conditions for technical efficiency hold only if the constraint on third-period water availability is non-limiting. This result illustrates the limitations of applying neoclassical production functions, which presuppose technical efficiency, to the intraseasonal water allocation problem.

When water allocation between multiple crops are of concern and intraseasonal water supply is constraining, economic theory suggest that water allocation does not need to be technically efficient. To optimise intraseasonal water use a multiple period model is necessary where the impact of decisions in previous periods are linked to current period decisions.

2.1.4 IMPLICATIONS

The economic theory of water use optimisation has some serious implications for optimising water use between multiple crops under conditions of limited water supply. The fact that optimal irrigation schedules need not be technically efficient when restrictions are imposed on the intraseasonal distribution of water implies that the optimisation has to allow for these technical inefficiencies. Two options are available. The first is to optimise a continuous response function that relates crop yield as a function of soil-moisture status. Examples include dynamic programming (Tilahun and Raes, 2000) and linked simulation optimisation procedures (Botes, 1994). However, even with the advances in computer technology, these procedures still lack the general ability to incorporate realistic soil moisture budgets and/or multiple crops. As a second alternative, crop growth simulation models can be used to generate information on a range of irrigation schedules that can be incorporated into linear programming models to optimise water use (Bernardo, Whittlesey, Saxton and Basset, 1986).

In the next section alternative methods of optimising water use in South Africa are reviewed.

2.2 EXAMPLES OF WATER USE OPTIMISATION

2.2.1 SOUTH AFRICAN RESEARCH

Viljoen, Symmington, Botha and Du Plessis (1993) used a crop growth simulation model to simulate the impact of alternative deficit irrigation scheduling strategies on water use and crop yield. The outputs of the model were used to estimate polynomial crop water production functions. Point estimates on these functions were then included in an optimisation model to optimise water use between multiple crops under conditions of limited water supply in Vaalharts. Clearly these researchers did not account for the dynamic aspects of water use optimisation with their single period model. Furthermore the impact of water deficits on crop yield during different time periods of the growing season was ignored.

Mottram *et al* (1995) were the first to account for the impact of water deficits in different crop growth stages when optimising water use with a linear programming model. These researchers estimated the crop water requirements and allowed for different combinations of 10 mm deficits in each of the growth stages in their programming model. Crop yield was estimated for each combination using an additive law of calculating crop yield as a function of ET deficits. Two critical assumptions were made by these researchers. Firstly they assumed that water use in any of the crop growth stages is independent of the other. Thus, the influence of irrigation decisions early in the season have no influence on decisions made later in the season. Secondly they assumed that reductions in ET are proportional to reductions in applied water. Thus, these researchers did not account for increasing water use efficiencies as the crop is deficit irrigated.

Grové and Oosthuizen (2002) optimised agricultural water use while quantifying economic environmental tradeoffs of maintaining instream flow requirements. Rather than generating discrete activities of alternative deficit irrigation schedules these researchers optimised a continuous function that relates ET to crop yield. The Stewart multiplicative function has the property that it models more than proportional yield reductions if the crop is stressed in more than one crop growth stage. Increasing water use efficiencies as the crop is deficit irrigated were modelled using procedures developed by Willis (1993) whereby efficiencies are assumed to increase linearly between maximum water application and a given maximum allowed deficit. Although these researchers were able to model increasing irrigation efficiencies as the crop was deficit irrigated they did not link the water budgets in different crop growth stages.

The most sophisticated example of crop water use optimisation is the work done by Botes (1994). This researcher linked a crop growth simulation model to an optimisation procedure to quantify the value of irrigation information for decision-makers under risk. Although it is the most sophisticated treatment of optimising water use in South Africa, it is not very practical to optimise water use between multiple crops. Furthermore it will be difficult to include constraints related to a whole-farm situation within a water user association in such a framework.

Various other researchers optimised agricultural water use by means of LP or DLP (Hancke and Groenewald, 1972; Van Rooyen, 1979; Brotherton and Groenewald, 1982; Backeberg, 1984; Oosthuizen, 1995; Maré, 1995; Louw and Van Schalkwyk, 1997). However, these researchers did not include deficit irrigation as a water use optimising strategy.

2.2.2 International Research

Benli and Kodal (2003) emphasised the importance of using non-linear programming techniques to optimise water use under limited water supply conditions. These researchers estimated non-linear benefit functions from crop production functions, using the output from IRSYS. The benefit functions were then optimised to determine optimal allocation of water. The approach is therefore similar to that of Viljoen *et al* (1992) except for the fact that Benli and Kodal (2003) did not approximate the functions with linear programming.

The relationship between net irrigation requirement and gross application is influenced by the uniformity by which the irrigation system applies water (Ascough, 2001). Li (1998) showed how crop yield of a single crop is affected by the uniformity of sprinkler irrigation systems and the resulting optimal level of water applied.

De Juan, Tarjuelo, Valiente and García (1996) developed a decision model for optimal cropping patterns taking irrigation uniformity into account.

Dynamic Programming (DP) is frequently used to optimise crop water use under limited water supply conditions. Recent applications include Shangguan, Shao, Horton, Lei, Qin and Ma (2002) who applied multilevel optimisation through the use of DP. The first level, is to optimise water irrigation schedules for a single crop. With the second level water is allocated between multiple crops and at the third level between subregions.

This approach may become cumbersome if one wants to incorporate the modelling procedure within a dynamic linear programming framework to optimise irrigation investment decisions over time. Futhermore Shütze, de Paly, Wöhling and Schmitz (2005) caution the use of DP programming because of simplifying assumptions made to cope with the problem of dimensionality.

Bernardo, Whittlesey, Saxton and Bassett (1986) applied the theoretical framework for optimising water use between multiple crops discussed earlier in this chapter through the use of a crop growth simulator to generate activities for a LP model. What makes this procedure attractive is the fact that it is relatively easy to represent a whole-farm situation in an LP. Furthermore due to the discrete activities included in the model it will be possible to quantify the production risk associated with each irrigation schedule which can be incorporated into the LP model taking whole-farm considerations into account.

2.3 SKELETON MODELS

Many irrigation project feasibility studies (Backeberg, 1984; Louw and Van Schalkwyk, 1997; Oosthuizen, 1995; Maré, 1995) used dynamic linear programming. Most of these applications embody very specific matrix structures applicable to the agricultural situation in which they were developed. McCarl (1982) cautioned that models such as these are not very applicable in other situations due to a lack of generality.

A skeleton model or generalised model represents the logical structure and includes only the basic parameters of the real system. However, when "coupled" with data from an individual farm it becomes a powerful tool to evaluate the unique situation of a specific farm (Blackie and Dent, 1974). According to Dent (1975) it is literally a framework that will absorb the flesh of a whole range of systems. Kuhlmann and Brodersen (2001) argued that the adoption of such models can be increased by linking the skeleton model to domain data bases to obtain knowledge-based models. Applicability for a specific farmer/user can be achieved by allowing the user to change input parameters.

REPFARM (McCarl, 1982) is an example of a representative farm model that includes a more flexible representation of different situations. Louw (1996) developed the OPTIMA model within a South African perspective to make DLP more accessible. However, this model was not developed with the specific aim of optimising water use.

2.4 DYNAMIC LINEAR PROGRAMMING

Farm investment decisions (e.g. perennial crops, machinery selection problem, livestock and/or irrigation investments) are basically more challenging to model than seasonal or annual (short-run) cropping decisions. This is because they involve multiple year dynamic elements. Therefore, they have gestation periods extending beyond a single agricultural year, and their costs and returns are not uniformly distributed over time (Hazell and Norton, 1986). In general, dynamic concerns arise (McCarl and Spreen, 1997) when decision-makers face: a) binding financial constraints which change with time; b) a production situation in which current actions impact the productivity of future actions; c) a need to adjust over time to exogenous stimulus; d) future uncertainty and / or e) an exhaustible resource base. The possible methodologies that can be used for production and investment decisions in dynamic models to examine firm growth include simulation, dynamic programming, and multiperiod linear programming (Boeljhe and

White, 1969). All these models have found several applications in agricultural activity and other studies. However, only multiperiod linear programming will be discussed.

DLP is an alternative to capital budgeting in complex investment or development situations where one might want to consider simultaneously: the choice of one or more items of irrigation systems and/or types of perennial cropping from a list of contenders; the timing of investments in relation to likely supplies of capital funds, either owned or borrowed; and/or the feasibility of any development or investment programmes in relation to existing supplies of fixed factors of production. Rather than laboriously preparing capital budgets to answer the above list of investment programme, a dynamic linear programming can be employed as a most efficient analytical procedure (Raes, 1977). Specifically, there are two basic approaches to modelling investment decisions in linear programming models (Hazell and Norton, 1986; McCarl and Spreen, 1997):

a) *Stationary equilibrium approach*: where it focuses on the optimal level of investment that should be attained in an equilibrium state. Here, the firm is assumed to operate in a steady state manner, repeatedly making identical decisions in all time periods and thus a "representative" single period representation is therefore implemented.

b) *Multiperiod linear programming*: where it provides an optimal growth strategy for the farm that gives both longer-term investment levels and the optimal adjustment path that should be pursued in achieving those goals. These types of models are also referred to as disequilibrium models.

McCarl and Spreen (1997) further distinguished between unknown and known life investments. Known life represents situations where once begun the activity begun will require resources and/or produce resources for a known number of periods. Unknown life refers to situations where permission activities are used to permit a linkage from one period to another. Thus, the activity can be terminated during any time period in the planning horizon.

2.4.1 DISEQUILIBRIUM – KNOWN LIFE

McCarl and Spreen (1997) give the following specification and explanation of a disequilibrium known life programming model. The mathematical specification of the model given the assumptions that all enterprises have the same known lifespan and that resource use and returns are independent of the year in which the activity began, is as follows:

$$\text{Max} \quad \sum_t \sum_j (1+r)^{-t} C_{jt} X_{jt} \quad + \quad (1+r)^{-t} \sum_e \sum_j F_{je} I_{je}$$

$$\text{Subject to (s.t.)} \quad \sum_e \sum_j A_{ije} X_{j,t-e} \quad \leq b_{it} \qquad \text{for all } i \text{ and } t$$

$$X_{j,-e} = X^{*}_{j,-e} \quad \text{for all } e > 1 \text{ and all } j$$

$$-\sum_{e} \sum_{j} X_{j,T-e} + I_{je} = O \quad \text{for all } e < K \text{ and all } j$$

$$X_{jt} \quad I_{je} = O \quad \text{for all } j, t \text{ and all } e < K$$

Here t is the year identifier; T is the last year in the model; j identifies alternative variables; e indexes the elapsed age that an enterprise is utilised; K is the life of an enterprise (i.e., the number of periods after starting the enterprise that resources are used); i indexes resources; r is the discount rate; C_{jt} is the profit from initiating variable X_{jt} in year t; X_{jt} is the number of units of alternative j initiated in year t; F_{je} is the terminal value of X_{je} after the explicit time period in the model lapses; I_{je} is the number of units of X_j which are e years old; A_{ije} is the usages of resource i by the jth alternative when it is e years old; b_{it} is the endowment of resource i in year t; and $X^{*}_{j,-p}$ is the initial condition giving the amount of X_j done p years before the model begins.

The model maximises net present value of activity from years 0 through T plus the terminal value of in-process inventory. Annual profits are converted to present value by multiplying by the discount factor. The model assumes the profits (C_{jt}) are collapsed into the period when the X_j variable is initiated. This is done by calculating the term C_{jt} as

$$c_{jt} = \sum_{e} (1+r)^{-(t+e-1)} h_{je}$$

$$\text{where } e \leq \{K-t, T-t\}$$

where h_{je} is the net profit from X_{jt} when it is e years old. The inequality for e accounts for cases where the life of the enterprise extends beyond the time horizon.

The second term of the objective function gives the terminal value of enterprises not entirely completed during the years the model explicitly covers. For example, enterprises begun in the last year explicitly modelled are valued at F_{j0}, since they will be one year old in the period following the model. The F_{je} terms depict a future stream of profits to activities lasting beyond the model horizon discounted back to year T.

The first model constraint requires resource use to be less than or equal to resource availability in that year. Annual resource use depends upon enterprises begun in the current time period as well as items which began up to K years in the past. Thus, the summation subscripting in the equation adds all variables which are of age 1 to K years old in the current year (t). Resource use is assumed to depend only on the elapsed age (e) of the activity. Each alternative (j) once committed will always exist for years $t+1$ to $t+K$ using an a priori specified amount of resources (A_{ije}) each year. The next constraint set specifies the initial conditions: i.e., the amount of enterprises undertaken before the model was started which use resources during the time period covered by the model. The last constraint set adds up in process inventory at the end of the explicit time horizon setting the variable Ije equal to the amount of X_j which is e years old in the final model year and will extend into future years, thus the $e=K$ case is not included.

The formulation assumes all enterprises have the same life. This clearly is not necessary and will be relaxed in the example. The assumption could be relaxed in the general model by adding a subscript j to the e parameter which would depict the life of the j^{th} activity. The model also assumes equal length periods.

The above specification ignores any transfer activities from one year to another. However, an activity in one year can contribute to capital supply in the following year. That is, it will have a positive coefficient of capital restriction of the given or same year, but a negative coefficient for the capital restriction in the year following. The negative coefficients will be a magnitude expressing the net profit per unit of activity in the given year. In this way profits in one year can be added to the supply of capital available in later years. However, considering the funds that will be withdrawn for consumption in a given period before they are available for production in the following period is important (Heady and Candler, 1960; Boehlje and White, 1969). A specification that accounts for linkages between years will alter the objective function in such a way that it will optimise the present value of cash flow in the terminal time period plus terminal values.

2.4.2 CALCULATION OF TERMINAL VALUES

Terminal values are of concern if the DLP model does not contain an infinite time horizon or conditions where all dynamic enterprises stop at the end of the planning horizon (McCarl and Spreen, 1997). When terminal values are included in the specification it will insure that investment decisions are not penalised when they are initiated near the end of the planning horizon. The model will therefore be more realistic.

Either a positive or normative can be used to estimate terminal values (Raes, 1970). With the normative approach one needs to value assets in accordance with their market value. Du Toit (1993) used the market value of farms with similar composition of orchards to determine terminal values. Such an approach will be impractical if one intends to develop a generalised model with minimum inputs.

The positive approach assigns a value equal to the present value of the future income stream. More specifically Raes (1970) calculates the terminal value as:

$$TV_{jk} = \max_{n}\left\{R_{m+1}/(1+r) + R_{m+2}/(1+r)^2 + \mathrm{K} + R_{m+n}/(1+r)^n + A/r(1-r)^{n+1}\right\}$$

where TV_{jk} terminal value of activity j planted in year k

R net revenue of activity in same year

m elapse age of activity at the end of planning period

$m+n$ optimum replacement age of activity

A maximum annuity

The positive approach of calculating terminal values was used by Haile (2003).

2.5 PROCEDURES TO INCORPORATE RISK INTO MULTIPERIOD PROGRAMMING MODELS

Due to the limited availability of suitable algorithms to solve quadratic programming models, many researchers have focussed on linear alternatives such as MOTAD (Hazell, 1971) and Target-MOTAD (Tauer, 1983) to incorporate risk into mathematical programming models (Ortmann, 1989). DLP risk applications in South Africa include the research done by Nowers and Van Zyl (1991) and De Jager and Van Zyl (1991). Both used Target-MOTAD to incorporate risk into their DLP models. However, the assumptions about intra- and intertemporal correlation between alternative activities are difficult to infer given the limited amount of detail given.

Kaiser and Boehlje (1980) presented a framework to incorporate risk into DLP models using MOTAD and quadratic programming given the assumption that no intertemporal correlation exists and therefore the covariance between years is ignored. McCarl and Spreen (1997) cautioned the use of their framework to incorporate risk into DLP models using MOTAD.

With the advances in computer technology and the availability of modern non-linear solvers such as CPLEX even large quadratic programming models are solved easily. The remainder of this section will therefore focus on the quadratic programming specification.

A more comprehensive conceptual framework to incorporate risk into DLP models while recognising that both inter- and intratemporal correlations exist can be developed by realising how the expected value and the variance of a linear combination of random variables over multiple years are calculated.

The following equation is used to calculate the expected present value of the farm plan (Y) as the sum of discounted expected values occurring in different time periods (Bussey, 1978:382):

$$E[P_j] = \sum_{t=0}^{n} \frac{E[Y_t]}{(1+i)^t}$$

The variance of the farm plan is calculated as the sum of appropriately discounted variance and covariance matrixes as follows (Bussey, 1978:384):

$$V[P]=\sum_{t=0}^{n}\frac{\sigma_t^2}{(1+i)^{2t}}+2\sum_{=0}^{n-1}\sum_{\theta=1_{\tau+\theta}}^{n}\frac{Cov(Y_\tau Y_\theta)}{(1+i)^{\tau+\theta}}$$

Recognising that Y_θ and Y_τ are correlated outcomes of farm plans in periods τ and θ, the covariance between Y_θ and Y_τ is defined by the following relationship $Cov(Y_\theta, Y_\tau) = \rho_{\theta\tau}\sigma_\theta\sigma_\tau$ $(\theta \neq \tau)$ where $\rho_{\theta\tau}$ is the simple correlation coefficient and σ_θ and σ_τ are the standard deviations in the respective periods. Thus, correlation matrices such as those used in long-term simulation models (Richardson, Klose and Gray, 2000) to correlate random variables can be used to estimate the covariance matrix.

If you want to model independence between years the correlation matrix becomes zero and only the first part of the variance calculation is applicable. Note, however, that the discount factor is raised to the power of 2_t and not t (Bussey, 1978: 383).

Extending standard single period (E,V) formulations to a multiperiod model using the logic of equations (2) to calculate the present value of expected gross margins and equation (3) to discount the variance to present value results in the following model:

$$V=\sum_j\sum_t X_{jt}^2\sigma_{jt}^2 \Big/ (1+r)^{2t}+\sum_{k\neq j}\sum_j\sum_{p\neq t}\sum_t X_{kp}X_{jt}\sigma_{jtkp} \Big/ (1+r)^{t+p}$$

subject to: $\sum_j\sum_t \overline{C}_{jt}X_{jt} \Big/ (1+r)^t = \lambda$

with

- $\overline{C}_{jt}$ expected gross margin of activity j in period t
- X_{jt} variable denoting activity level j in period t
- σ_{jt}^2 variance of activity j in period t
- σ_{jtkp} covariance matrix between crops j and time periods t

The objective of the model is to minimise the present value of variance given a specified target gross margin (λ). Critical inputs to the model are the expected gross margins $(\overline{C},t)$, variance σ_{jt}^2 and covariance matrix (σ_{jtkp}).

2.6 CONCLUSIONS

Current methodologies used in South Africa to optimise water use between multiple crops under constrained water supply conditions are lacking. This is mainly due to their inability to account for dynamic relationships between different crop growth stages. These relationships are best described using crop growth simulation models. Simulation models can be used to generate alternative irrigation schedules that can be used to optimise water use between multiple crops. However, it is important to note that under constrained water supply conditions technically inefficient strategies should also be included. A major benefit of using crop growth simulation models is that these models can also be used to quantify production risk associated with alternative deficit irrigation schedules. The preferred method of incorporating risk into DLP models by South African researchers is Target MOTAD. However, their applications of the method is not transparent and in some cases result in single period specifications for each year of the planning horizon. Thus, there is a clear need to develop transparent procedures to incorporate risk in DLP models.

Long-term risk simulation procedures can be used to generate sequences of stochastic variables over the long term taking both intra- and intertemporal correlation into account.

The disequilibrium known life specification of DLP models has a logic structure that repeats itself from year to year. This property makes the model fairly easy to program given inputs regarding the known life of alternative activities.

CHAPTER 3

STUDY AREA

3.1 GENERAL DESCRIPTION AND LOCATION

The Vaalharts Irrigation Scheme is east of the Ghaap plateau, on the Northern Cape and North West Province border. The border is currently running through this scheme. The area covers about 36 950 ha, and is one of the largest irrigation areas in the world. Water is provided to some 680 farmers.

The scheme is supplied with water abstracted from the Vaal River at the Vaalharts Weir about 8 km upstream of Warrenton A canal is used to convey the water to the scheme. When the canal reaches the scheme it divides into two main canals, the north canal and the west canal. The north canal feeds the greater Vaalharts area of water, this includes places like; Jan Kempdorp, Tadcaster, Hartswater and Magogong. The west canal provides water to Ganspan, Hartsvallei and Bull Hills. These canals provide water to a network of feeder and community canals. Additionally there are drainage canals, draining water out of the scheme to the Harts River, west of the scheme.

A Water User Association (WUA) was formed to help the community carry out their water-related activities more effectively.

3.2 CLIMATE

Vaalharts Irrigation Scheme is located in a summer rainfall area. This area battles with low, seasonal and irregular rainfall. The irregular rainfall makes irrigation more important than would otherwise have been the case.

The average rainfall is 442 mm per year and is concentrated from October to April; January (71 mm) being the month with the highest rainfall (Viljoen *et al.*, 1992). The rainfall is mostly in the form of heavy thunder, although soft frontal rainfall also occurs, and hail storms are a common phenomenon (De Jager, 1994).

January seems to be the warmest month with maximum and minimum temperatures of 32.7 °C and 17.4 °C. July is the coldest month with a day temperature that can fall to 2.4 °C (Viljoen *et* *al.* 1992). Common to this area is the significant difference between the maximum and minimum temperatures as the seasons change.

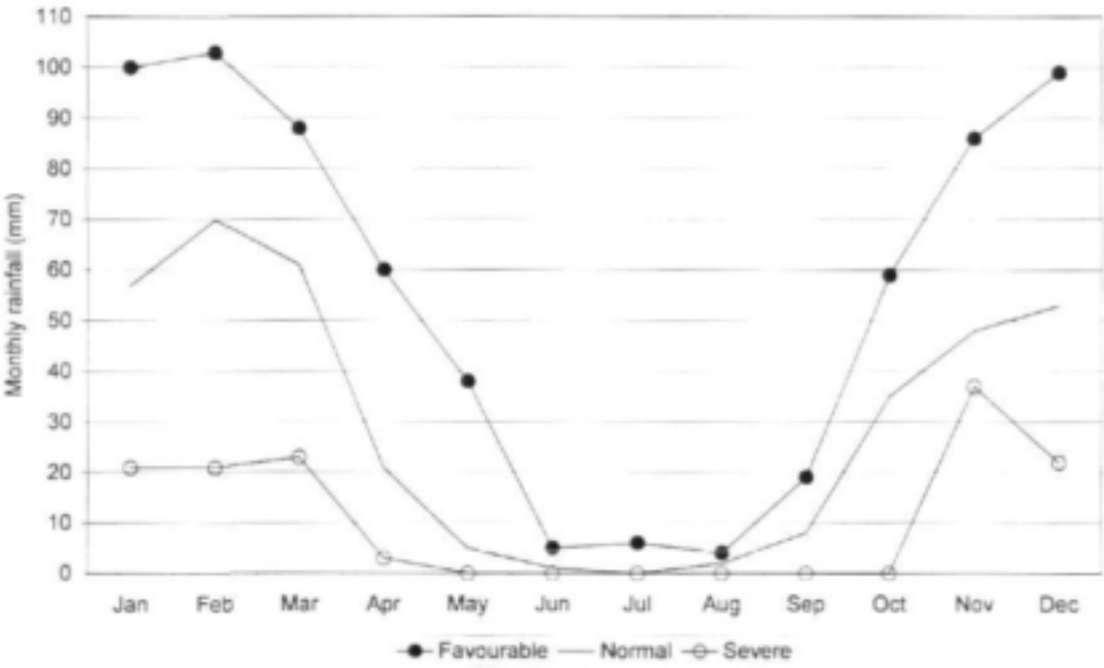


Figure 3.1: Monthly rainfall data from SAPWAT for the rainfall at the Jan Kempdorp weather station for years with normal, favourable and severe weather conditions.

The average precipitation in the summer months, October to February, differs between 9.1 and 9.6 mm/day, while in July precipitation is only 3.6 mm/day. The capacity of the canals in Vaalharts is 4mm/day which is less than desired (Viljoen *et al.*, 1992).

The weather data that is used in this study for the simulations were obtained from SAPWAT. Figure 3.1 shows the average monthly rainfall for years with normal weather conditions as well as years with favourable and severely unfavourable weather conditions. It is clear that Vaalharts is in a summer rainfall area receiving the highest rainfall from November to March. The rainfall is the lowest from April to October. In some years (severe years) it did not rain at all in the months May to September.

The evaporation for these different weather scenarios is given in Figure 3.2. The highest ET_0 values are observed in the summer. There is a negative correlation between the rainfall and the evapotranspiration for the different years. The severe year has the highest ET_0 and the lowest rainfall. The favourable year has the lowest ET_0 values and the highest rainfall. However,, per month the highest ET_0 measurements are in the summer months, which also receive the highest rainfall.

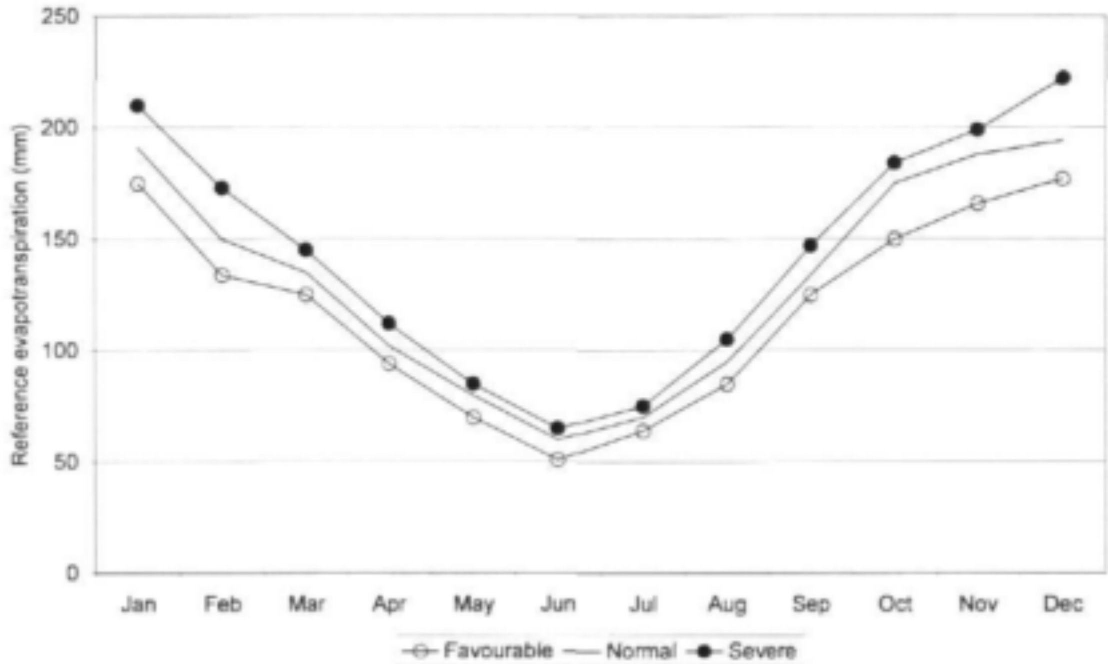


Figure 3.2: The monthly evaporation for three different weather years (normal, favourable and severe) at the Jan Kempdorp weather station. Data obtained from the SAPWAT irrigation planning programme.

3.3 SOIL

The two main types of soil found in Vaalharts are Hutton/Mangano and Clovelly/Sunbury (Herold and Bailey, 1996). The soils have a high sand context, which leads to compactation and puts a constraint on potential root depth. The soil also has a low water holding capacity, low fertility, high bulk density and limited depth (Herold and Bailey, 1996; Streutker, 1977). According to Viljoen *et al.* (1992) the largest proportion (±70%) of soil is the Mangano type, which is a sandy loam with silt and clay contents that fluctuate between 10 and 16 per cent.

About 12.9 per cent of the area's soil depth is less than 0.9 m. More or less 10.9 per cent of the area's soil depth is between 0.9 m and 1.2 m, while 15.4 per cent of the soil depth is between 1.2 m and 1.8 m. The greater part of the scheme, 60.9%, has a soil depth of more than 1.8 m (Herold and Bailey, 1996).

3.4 WATER DEMAND, DISTRIBUTION AND ALLOCATION

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 m^3 per ha, resulting in an annual water use right of 209 744 720 m^3 for the north canal and 57 143 280 m^3 for the west canal (Van Heerden, 2001). Crop water requirement for the north and west canal are similar, the reason why so much more water is allocated to the north canal is that it provides water to a larger area.

The feeder canals are supplied directly by the two main canals. The farms optimised for this project are supplied with irrigation water from feeder 5 (TVV 5). Each feeder provides water for the community canals. Most of the community canals, which receive water via feeders out of the northern canal, provide water for six plots. Most of these community canals can supply water for two plots at a time due to limitations on community canal capacities. Therefore farmers need to take turns to water their plots. Each turn ("beurt") is 24 hours long. When it is a particular plot's turn it receives about 150 m^3 water per hour. Each week the farmers of a community canal fill in the water requested for the coming week. These forms are handed in before or on the Thursday before the water is needed.

Traditionally water is supplied for five and a half days, from Monday mornings to Saturday afternoons. Centre pivots enable farmers to irrigate any day of the week because labour is largely cut out. In other words, these farmers can now receive water any day of the week because the labour for irrigation is not a problem. The increase in the number of centre pivots will result in the increase in pressure from farmers on the water authorities to be supplied with water for seven days a week.

The total water use charge in Vaalharts is 8.77 cents per cubic meter of water which consists of a charge of 8.24 cents for irrigation water use, a catchment management charge of 0.5 cents per cubic meter and a water research charge of 0.03 cents per cubic meter of water. The farmer pays this tariff to the Vaalharts water users association. Part of this tariff is used by Vaalharts water to keep the canals in a good condition.

3.5 REPRESENTATIVE FARMS

Louw (2002) compiled representative farms for the Vaalharts irrigation scheme to determine the value of irrigation water. These representative farms are also used in this research. However, the areas of the farms were standardised on 25.7 ha plots to correspond with the physical farm sizes of the specific area that is modelled in this research. To evaluate the distribution of farm sizes in Vaalharts the database from Vaalharts Water is used. A database compiled by the National Department of Agriculture is used to determine distribution of crops and irrigation systems within specific farms.

3.5.1 FARM SIZE

Vaalharts Water uses the water administration system (WAS) to administrate water allocations in the region. The Vaalharts Water database consists of the billing information of all the water users. More specifically the plot number (agricultural users), the name and initials of the person accountable for the payments, the physical address and the postal address are given in the database. The information in the database was used to estimate the total number of farming units and plots in each unit. The data were sorted according to the postal addresses, which enabled us to see the number of plots in each farming unit.

Six hundred and eighty five farming units were counted for the total irrigation scheme. Two hundred and twenty two (32%) were one-plot farms and a hundred and fifty (22%) were two-plot farms. The rest were 63 (9%) three-plot farms, 70 (10%) four-plot farms, 36 (5%) five-plot farms and 37 (5%) six-plot farms. The frequencies are available to well into the thirty-plot farms, but the six-plot farms are the last group of farms that is significant. These six groups of farms represent 84% of the total number of farm-units in the Vaalharts irrigation scheme.

Louw (2002) compiled small, medium, large and extra large representative farms for Vaalharts based on a sample of 38 farmers. Given a standard plot size of 25.7 ha small farms correspond to one plot, medium to three plots, large to five plots and extra large to nine plots. The representative farms of Louw (2002) were scaled proportionately to fit the scaled plot sizes of 25.7 ha.

3.5.2 CROP PRODUCTION

Figure 3.3 shows the percentage of one-plot, three-plot and five-plot farms producing a specific crop. Cash crops are by far the most important crops cultivated in Vaalharts irrigation scheme. The most commonly found cash crops are wheat/barley, maize, groundnuts and cotton. Wheat is a winter crop and is produced in rotation with maize and/or groundnuts. Maize and groundnuts grow in the summer and compete for resources. The specific area allocated to a specific crop is determined by product price expectations at plant. The low cotton prices have generally resulted in only a few farmers producing cotton.

Permanent crops that are produced in Vaalharts include lucerne, pecan nuts, grapes, olives and some other fruits. Of these permanent crops lucerne and pecan nuts are the most important. Olives do well in the irrigation scheme, but are not as popular as lucerne and pecan nuts. Unfortunately severe frost in 2003 damaged much of the citrus and other fruit orchards which resulted in a decline in the acreage under fruit.

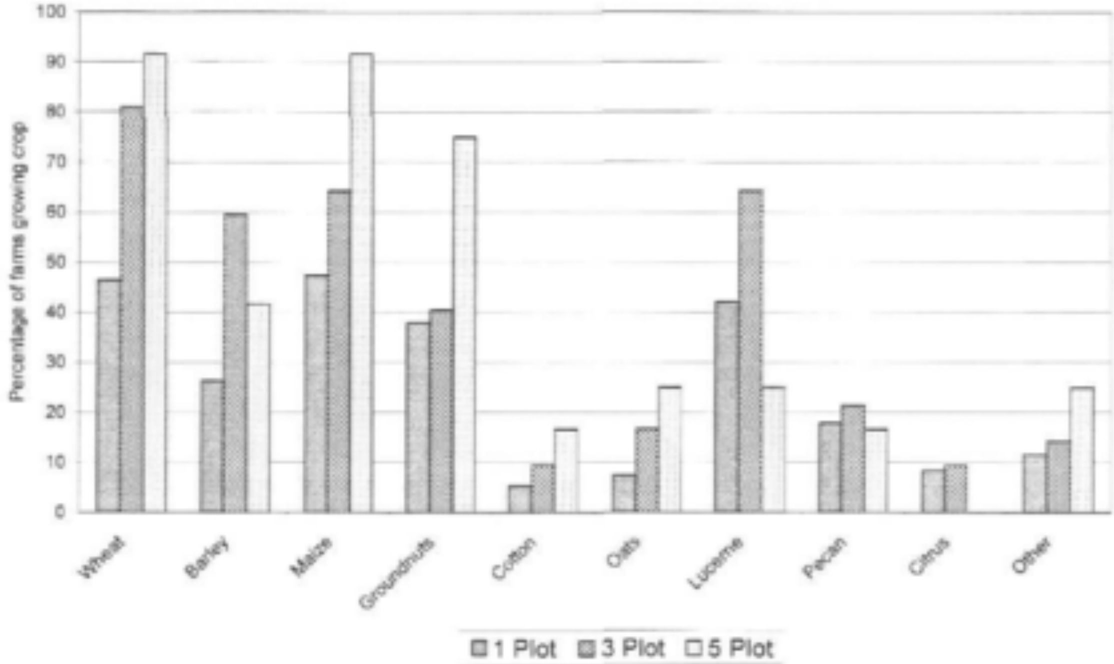


Figure 3.3: Percentage of one-plot, three-plot and five-plot farms growing a specific crop. (Source: Badenhorst, 2003).

Vaalharts was originally designed for flood irrigation. In the past few years centre pivot irrigation has increased tremendously. Table 3.1 gives the distribution of irrigation system by farm type. From Table 3.1 it is clear that on average about 67% of all the farms use flood irrigation while more or less 30% of all the farms use pivot irrigation. Thus, flood irrigation and centre pivot irrigation are the dominant methods of irrigation. Other irrigation systems such as micro- and drip irrigation are predominantly used to irrigate tree crops.

Table 3.1: Utilisation of irrigation system by farm size.

	Percentage of farm type utilising irrigation system (%)		
Irrigation system	1 Plot	3 Plot	5 Plot
Flood	76	60	66
Pivot	24	37	26
Other	0	3	9

Source: (Badenhorst, 2003)

3.5.3 *IRRIGATION REQUIREMENTS*

Irrigation water demand is defined as the amount of water that should be applied to a specific crop irrigation system combination. Each farmer is allocated 914 mm per ha water per annum which the user may distribute between crops. Seasonal crop water requirements for the most important crops are shown in Table 3.2

Table 3.2: Monthly SAPWAT estimated gross irrigation water requirements (mm.ha) for selected crops under flood and pivot irrigation in Vaalharts.

	Monthly gross irrigation water requirement (mm.ha)												
	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Total
Flood													
Late maize		120	60	240	240	60							720
Groundnut		60	120	120	240	240	60						840
Lucerne	240	300	240	240	120	60	120	120	60	60	120	120	1800
Pecan nuts	240	240	300	120	120	120	120	60	60	120	120	300	1920
Pivot													
Late maize		60	75	120	150	15							420
Groundnut		30	75	105	120	105							435
Lucerne	105	120	120	105	60	60	60	30	15	105	120	120	1020

From Table 3.2 it is clear that the gross water requirements vary from a low of 400 mm with centre pivot to a high of 1920 mm with flood. Annual crops require grossly between 420 to 435 mm water with centre pivot and between 720 and 840 mm with flood irrigation. The gross crop water requirement for late maize (both flood and centre pivot) is also less than that required for groundnut (flood and centre pivot). The difference of perennial crops irrigated by centre pivot and flood is substantial, e.g., the gross water requirements for lucerne flood is 1 800 mm, while for lucerne centre pivot it is only 1 020 mm. What is obvious from the table is that the water requirements for centre pivot are less than that of flood irrigation, because of efficiency differences in the irrigation systems.

3.5.4 CASH EXPENCES AND INCOME

The crops grown are the most important generators of income. The enterprise budgets for the most important crops are given in Appendix C. The overhead costs per annum of the one-plot, three-plot and five-plot farms are R47 000, R67 000 and R107 000 respectively. However, these costs do not include electricity, land rent, income tax and the water tariffs. Household expenses per annum are R27 000, R62 000 and R76 000 respectively for the small, medium and large farms while fixed liabilities per annum are on average R31 000, R54 000 and R163 000 respectively.

CHAPTER 4

DESCRIPTION OF THE MULTIPERIOD RISK PROGRAMMING MODEL AND APPLICATION IN VAALHARTS

4.1 GENERAL DESCRIPTION

To facilitate the general description of the multiperiod risk programming model, a schematic of the model components is given in Figure 4.1.

Data input for the deterministic programming model (Base Model) consists of domain inputs, water supply, resource availability and use and financial parameters. One of the features of mathematical models is that a specific mathematical equation is able to capture the general relationship between variables and the right hand side. The calculation procedure (logic) is then applied to all the entities over which the mathematical equation is defined. The size of the programming model is to a large extent determined by the number of entities over which equations are specified. Domain inputs include indices to classify water resources, abstraction points, farms, crops, management options, production areas, resources and conveyance canals. The time horizon and within year time periods over which resource use is calculated are also specified in this section.

Water supply parameter tables are used to link conveyance canals to each other and to indicate abstraction points on each conveyance system. Information is also specified to link a specific farm to a specific water source (abstraction point). The delivery capacities of the canals, maximum abstraction capacities and storage capacities are also specified.

Resources are committed each year to annual production activities and to long-term crops depending on the life cycle of the crop. Thus, resource use is not only determined by optimised cropping activities, but also the resources that are already committed to the production. In order to calculate parameters on input use and availability of production possibilities for each year in the analysis the use has to specify the areas utilised, the elapsed lifecycles, the maximum length of the cycles and resources used over the lifespan of a crop.

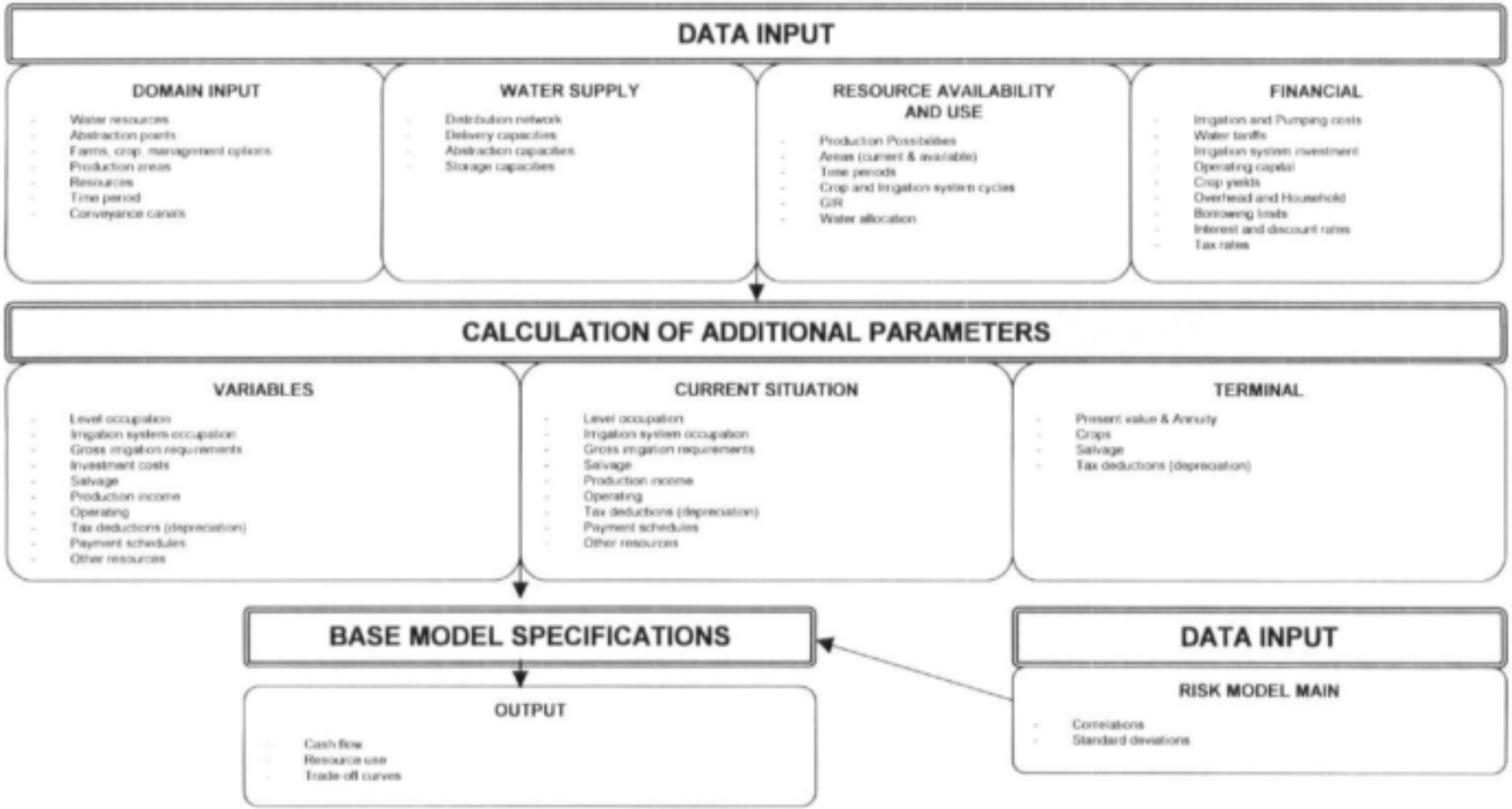


Figure 4.1: Schematic representation of the different components of the mathematical programming model.

Financial inputs necessary are the costs of obtaining and supplying water to the crops, irrigation system investment costs and salvage income, crop yield and prices, overheads and household expenses. The model also allows for borrowing activities and the limits on these activities must be specified. Interest, discount and tax rates are also specified in this section.

A modelling procedure was adopted whereby the user has to specify minimum inputs for the model. Standard DLP applications require that resource use, production income and expenditures, etc. over the planning horizon should correspond to the time period within the life cycle of the crop when it occurs. For example, if it is optimal to plant lucerne in year 1 and year 2 the resources used in the second year of the lucerne lifecycle established in year 1 should compete with the resources used in the first year of the lucerne established in year 2 and so forth. The main function of the data manipulation part is to generate data tables from the input parameters that fulfil in the above requirement. Although this procedure is somewhat cumbersome it provides an easy way of verifying procedures compared to a model where it is done when the matrix is generated (equation specification). Thus, the adopted modelling procedure simplifies the model specification part.

Manipulation of data is done for both the current situation (resources already committed) and other production activates. Terminal values are also calculated based on a normative approach which takes any cash flow streams past the planning horizon into account.

The equations used to generate the matrix for the optimisation model is first specified for a deterministic model. For the stochastic version of the model additional inputs required are the correlation matrix and standard deviations of activity Outputs include cash flows, resource use, shadow values of binding constraints and risk trade-off curves.

In the next sections the different components of the mathematical programming model are discussed in more detail.

4.1.1 DOMAIN OF THE MODEL

The domain of the programming model is determined by the number of sets and the data input. In order to define the sets appropriately it is necessary to have a clear understanding of the water allocation problem at hand. To facilitate the description of the domain of the model and also how to input data for the model, Figure 4.2 is used to represent the water redistribution network of a hypothetical water user association.

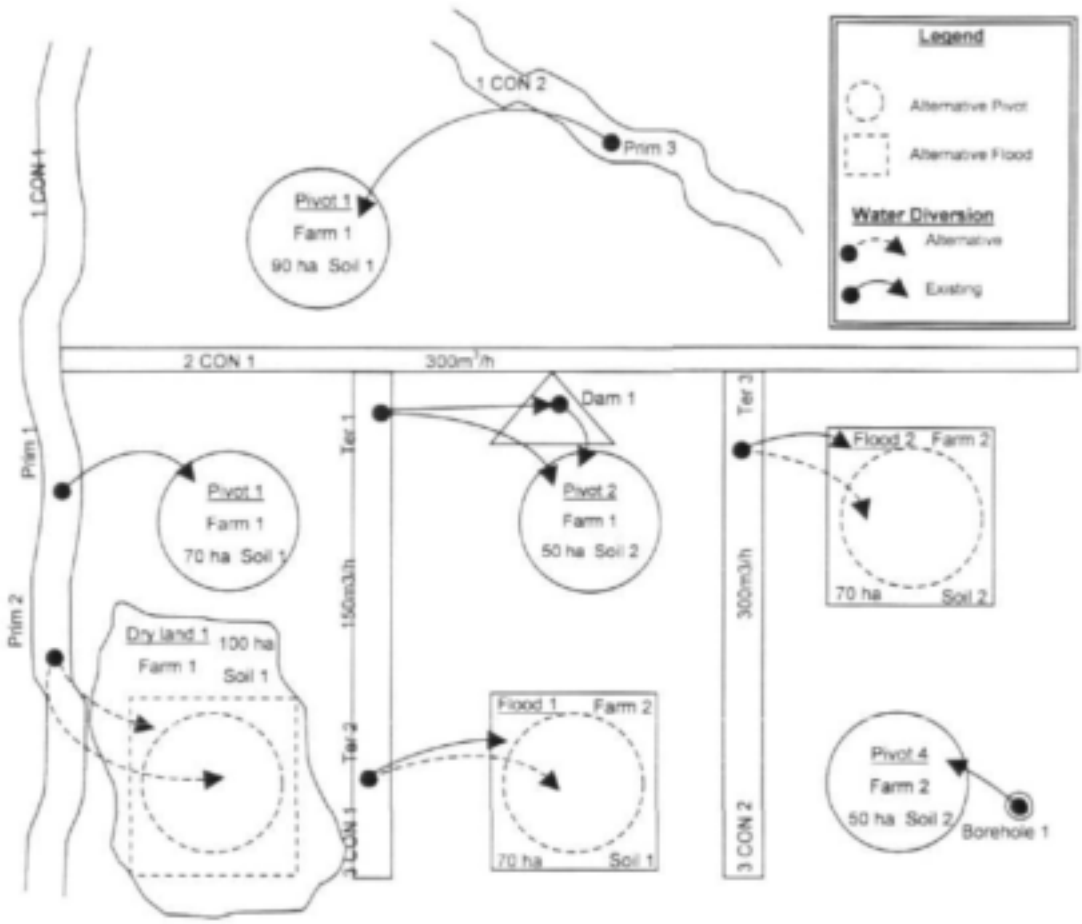


Figure 4.2: Schematic representation of a hypothetical water distribution network.

Figure 4.2 represents a scheme where water needs to be allocated from two primary water sources conveyed to the scheme with conveyance 1 CON 1 and 1 CON 2. Conveyance 1 CON 2 has only one user with an irrigation potential of 90 ha of which 90 ha is already utilised by centre pivot irrigation. Conveyance 1 CON 2 conveys water to multiple users with different irrigation possibilities (flood and pivot). Hundred hectares of irrigable soil (Dryland 1) with a possible offtake point (primoff) from 1 CON 1 can be utilised by farmer 1 with either centre pivot or flood irrigation. Pivot 4 does not utilise any water distributed from the primary water sources but uses a borehole as irrigation supply. Water is supplied to Pivot 2 from a farm storage dam or direct from 2 CON 1 conveyance.

The sets used to control the domain of the programming model is given below.

```
SETS
g  geographical information identifiers
   /dryland1                dryland production areas
    pivot1  *pivot4         pivot irrigation areas
    flood1  *flood2         flood irrigation areas
    teroff1 *teroff3        water offtakes at farm - tertiary conveyance
    primoff1*primoff3       water offtakes at farm - primary conveyance
    dam1                    farm dams
    borehole1               boreholes/
pg(g)  geographical areas related to crop production
```

```
   /dryland1
    pivot1  *pivot4
    flood1  *flood2/
ig(g)  geographical areas related to irrigation production
   /pivot1  *pivot4
    flood1  *flood2/
ws(g)  geographical irrigation water source identifiers
   /teroff1*teroff3
    primoff1*primoff3
    borehole1
    dam1/
pws(ws)  geographical main irrigation water source identifiers
   /teroff1*teroff3
    primoff1*primoff3
    borehole1/
off(ws) all water abstraction offtakes from conveyance structure
   /teroff1*teroff3
    primoff1*primoff3/
dam(ws) all farm dam storage identifiers
   /dam1/
bore(ws) all boreholes identifiers
   /borehole1/


f  farms
   /farm1*farm2/
c  crops
   /cropA
    cropB/
st(c) cash crops
   /cropA
    cropB /
m  management alternatives
   /m1/
r  alternative resource uses - excluding irrigation
   /labour, tractor/
t  years in planning period
   /y1*y4 /
wt time periods within t to specify water demand
   /wt1*wt3/
l  alternative interest rates
   /borrow_ope, borrow_inv, invest_bank/
p  production possibilities
   /dry
    flood
    pivot/
dry(p)  dryland production possibilities
   /dry/
irri(p)  irrigation production possibilities
   /flood
    pivot/
con  all conveyance identifiers
   /1con1*1con2            primary conveyance
    2con1                  secondary conveyance
    3con1*3con2            tertiary conveyance/
prim(con) primarary conveyance identifiers
   /1con1*1con2/
sec(con) second level of conveyance structures
   /2con1/
ter(con) tertiary conveyance identifiers
   /3con1*3con2/
ALIAS (t,pt,it)
ALIAS (c,c1)
ALIAS (st,st1)
ALIAS (pg,pg1)
ALIAS (p,p1)
ALIAS (m,m1)
ALIAS (con,con1,con2)
ALIAS (irri,irri1);
```

The names of all the different production areas (fields) are contained in set `pg` with sub set `ig` identifying the identifiers which are related to irrigation production. Set `ws` specifies all the water sources with `pws` specifying the water sources that supply water directly to an irrigation system. The farm storage dams are not included because they are classified as indirect water sources (`dam (ws)`). Furthermore the water sources are classified according to offtakes from the conveyance system (`off`) and boreholes (`bore (ws)`). The different levels of the conveyance system are specified by sets `prim`, `sec` and `ter`.

The farms in the region, crops grown and the alternative resources used by the farms are given in sets `f`, `c` and `r` respectively. Set `r` does not include irrigation water as a resource, because it is treated separately due to the complexity surrounding the supply of water to an irrigation system. Each production area (`pg`) can be utilised by irrigation production possibilities (`irri`) or dryland (`dry`).

The length of the planning horizon is specified with set `t` and the time periods within the year is given by set `wt`. Set `wt` determines the time interval for which irrigation water requirements and other resources must be specified.

4.1.2 DATA INPUT PARAMETERS

Once the domain of the model is specified, one needs to input the data through parameter tables. Some parameter tables are used to design the water distribution network by linking different conveyance canals, abstraction points, production areas and farms to each other.

4.1.2.1 Water supply

One of the unique characteristics of the skeleton model is that it is able to represent different water supply alternatives easily through the way inputs are specified. The model is able to keep track of the water flow through the conveyance system from the source to the irrigations field. A hierarchal approach is adopted to model water flow. With this approach higher order conveyance systems can only supply water to lower order conveyance structures. The following inputs are used to model water supply.

```
TABLE
prim_to_sec(con,con1) link primarary to secondary conveyance
              2con1
1con1            1
1con2
;
*
TABLE
sec_to_ter(con,con1) link secondary to tertiary conveyance
              3con1       3con2
2con1            1           1
;
```

```
*
PARAMETER
con_to_con(con,con1,con2) link primarary to secondary to tersiary conveyance;
con_to_con(con,con1,con2)= prim_to_sec(con,con1)*sec_to_ter(con1,con2);
option con_to_con :0:2:1;
display con_to_con;
*
TABLE
con_to_off(con,off) link conveyance to offtakes
         primoff1   primoff2   primoff3   teroff1   teroff2   teroff3
1con1           1          1
1con2                                1
3con1                                          1         1
3con2                                                              1
;
*
TABLE
pg_to_ws(pg,ws) link production area to primarary water supply source
         primoff1   primoff2   primoff3   teroff1   teroff2   teroff3   dam1
dryland1                   1
Pivot1          1
Pivot2                                         1                           1
Pivot3                               1
Pivot4
Flood1                                                   1
Flood2                                                             1
+
        borehole1
Pivot4          1
;
*
TABLE
dam_to_ws(dam,ws)   link dam storage to offtake at water supply source
          teroff1
Dam1            1
;
*
TABLE
pg_to_f(pg,f) link farm to production areas
            farm1      farm2
dryland1        1
Pivot1          1
Pivot2          1
Pivot3          1
Pivot4                     1
Flood1                     1
Flood2                     1
;
*
PARAMETER
f_to_ws(f,ws) link farm to water source;
f_to_ws(f,ws)=sum(pg,(pg_to_f(pg,f)*pg_to_ws(pg,ws)));
display f_to_ws;
*
PARAMETER
concap(con) conveyance capacity - m3 per hour
/1con1      110000
1con2       120000
2con1        21000
3con1         3100
3con2         3200/
;
*
TABLE
wscap(ws,irri) maximum abstraction capacity - m3 per time period wt
            flood      pivot
teroff1                  312
teroff2       321        322
teroff3       331        332
primoff1                 112
primoff2      121        122
primoff3                 132
```

```
borehole1                412
dam1                     512
;
*
TABLE
damwscap(dam,ws) maximum abstraction capacity - m3 per time period wt
          teroff1
Dam1          531
;
*
PARAMETER
damcap(dam) storage capacity of dam - m3
/dam1         5000/
;
*
PARAMETER
level_ini(dam) initial dam level - m3
/dam1            5/
;
```

Table prim_to_ter specifies which of the primary water conveyance is linked to secondary conveyance structures. The link between secondary and tertiary conveyance is specified with Table sec_to_ter. The information contained in these two parameters allows for the link between primary, secondary and tertiary conveyance as calculated with parameter con_to_con.

Water abstraction points (offtakes) are linked to the conveyance system through the specification of Table pg_to_off. Each offtake can be linked to a production area or if the water source is not an offtake the production area can be linked to a borehole or dam through the specification of Table pg_to_ws. Water supply to production area pivot 2 can either be from teroff1 and/or dam1. In order to be able to pump water into the farm storage dam, the farm dam needs to be linked to a water source through the specification of Table dam_to_ws.

The last input data necessary to keep track of water flow from a primary conveyance structure to a specific conveyance structure to a specific irrigation field belonging to a specific farm is table pg_to_f and the calculation of parameter f_to_ws.

Next, the parameters used to specify the capacity constraints on the water supply system are specified. Parameter concap is used to input the capacities of the primary, secondary and tertiary conveyance. Table wscap specifies the last link between a water source and an irrigation system. For instance, if water is abstracted from teroff1 into the dam, the last link is represented from the dam to the irrigation system. The link between the dam and the water source is specified by table damwscap. The storage capacity of the dam and the initial water level of the dam is specified through parameters damcap and level_irri respectively.

4.1.2.2 Resource availability and use

Resource use is not only determined by optimised activity levels, but also the current situation. The inputs necessary to model resource use are given below.

```
TABLE
pg_to_p(pg,p) link production areas to production possibilities
               dry      flood      pivot
dryland1        1         1          1
Pivot1                               1
Pivot2                               1
Pivot3                               1
Pivot4                               1
Flood1                    1          1
Flood2                    1          1
;
*
TABLE
c_to_p(c,p) link crop to irrigation production possibilities
               dry      flood      pivot
cropA           1                    1
cropB                     1          1
;
*
PARAMETER
areas(pg) hectares of each production area - ha
/dryland1      100
Pivot1         110
Pivot2         120
Pivot3         130
Pivot4         140
Flood1         150
Flood2         160/
;
*
TABLE
cur_irri_ha(pg,p) current production possibilities - ha
             pivot
Pivot1          55
Pivot2          60
Pivot3          65
Pivot4          70
;
*
TABLE
cur_crops_ha(pg,p,m,c) hectares of current crop production - last year is year
                              cropB
Pivot1  .pivot.m1                55
Pivot2  .pivot.m1                60
Pivot3  .pivot.m1                65
Pivot4  .pivot.m1                70
;
*
TABLE
cur_irri_cycle(pg,irri) years of investment - begining of year
             pivot
Pivot1           1
Pivot2           2
Pivot3           3
Pivot4           1
;
*
TABLE
cur_crop_cycle(pg,c) years of current crop production - beginning of year
             cropB
Pivot1           1
Pivot2           2
Pivot3           3
```

```
Pivot4          1
;
*
PARAMETER
crop_cycle(c) length of crop cycle - years
/cropA          1
cropB           3/
;
*
PARAMETER
irri_cycle(irri) economic life of irrigation system - years
/flood          1
pivot           3/
;
*
TABLE
grow(wt,c) growing season of crops
            cropA       cropB
wt1           1           1
wt2                       1
wt3                       1
;
*
TABLE
gir(pg,irri,wt,m,c,pt) gross irrigation requirement - units per time period
                              cropA.y1    cropB.y1     cropB.y2     cropB.y3
dryland1.flood.wt1.m1                         1211         1221         1231
dryland1.flood.wt2.m1                         1212         1222         1232
dryland1.flood.wt3.m1                         1213         1223         1233
dryland1.pivot.wt1.m1             2111        2211         2221         2231
dryland1.pivot.wt2.m1             2112        2212         2222         2232
dryland1.pivot.wt3.m1             2113        2213         2223         2233
Pivot1  .pivot.wt1.m1            12111       12211        12221        12231
Pivot1  .pivot.wt2.m1            12112       12212        12222        12232
Pivot1  .pivot.wt3.m1            12113       12213        12223        12233
Pivot2  .pivot.wt1.m1            22111       22211        22221        22231
Pivot2  .pivot.wt2.m1            22112       22212        22222        22232
Pivot2  .pivot.wt3.m1            22113       22213        22223        22233
Pivot3  .pivot.wt1.m1            32111       32211        32221        32231
Pivot3  .pivot.wt2.m1            32112       32212        32222        32232
Pivot3  .pivot.wt3.m1            32113       32213        32223        32233
Pivot4  .pivot.wt1.m1            42111       42211        42221        42231
Pivot4  .pivot.wt2.m1            42112       42212        42222        42232
Pivot4  .pivot.wt3.m1            42113       42213        42223        42233
Flood1  .flood.wt1.m1                        51211        51221        51231
Flood1  .flood.wt2.m1                        51212        51222        51232
Flood1  .flood.wt3.m1                        51213        51223        51233
Flood1  .pivot.wt1.m1            51111       51211        51221        51231
Flood1  .pivot.wt2.m1            51112       51212        51222        51232
Flood1  .pivot.wt3.m1            51113       51213        51223        51233
Flood2  .flood.wt1.m1                        61211        61221        61231
Flood2  .flood.wt2.m1                        61212        61222        61232
Flood2  .flood.wt3.m1                        61213        61223        61233
Flood2  .pivot.wt1.m1            61111       61211        61221        61231
Flood2  .pivot.wt2.m1            61112       61212        61222        61232
Flood2  .pivot.wt3.m1            61113       61213        61223        61233

;
*
TABLE
res_use(r,pg,p,wt,m,c,pt)  resource use by the crops - units per ha
                              cropA.y1    cropB.y1     cropB.y2     cropB.y3
labour.dryland1.flood.wt1.m1                  1211         1221         1231
labour.dryland1.flood.wt2.m1                  1212         1222         1232
labour.dryland1.flood.wt3.m1                  1213         1223         1233
labour.dryland1.pivot.wt1.m1      2111        2211         2221         2231
labour.dryland1.pivot.wt2.m1      2112        2212         2222         2232
labour.dryland1.pivot.wt3.m1      2113        2213         2223         2233
labour.Pivot1  .pivot.wt1.m1     12111       12211        12221        12231
labour.Pivot1  .pivot.wt2.m1     12112       12212        12222        12232
labour.Pivot1  .pivot.wt3.m1     12113       12213        12223        12233
labour.Pivot2  .pivot.wt1.m1     22111       22211        22221        22231
```

```
labour.Pivot2  .pivot.wt2.ml      22112      22212      22222      22232
labour.Pivot2  .pivot.wt3.ml      22113      22213      22223      22233
labour.Pivot3  .pivot.wt1.ml      32111      32211      32221      32231
labour.Pivot3  .pivot.wt2.ml      32112      32212      32222      32232
labour.Pivot3  .pivot.wt3.ml      32113      32213      32223      32233
labour.Pivot4  .pivot.wt1.ml      42111      42211      42221      42231
labour.Pivot4  .pivot.wt2.ml      42112      42212      42222      42232
labour.Pivot4  .pivot.wt3.ml      42113      42213      42223      42233
labour.Flood1  .flood.wt1.ml                 51211      51221      51231
labour.Flood1  .flood.wt2.ml                 51212      51222      51232
labour.Flood1  .flood.wt3.ml                 51213      51223      51233
labour.Flood1  .pivot.wt1.ml      51111      51211      51221      51231
labour.Flood1  .pivot.wt2.ml      51112      51212      51222      51232
labour.Flood1  .pivot.wt3.ml      51113      51213      51223      51233
labour.Flood2  .flood.wt1.ml                 61211      61221      61231
labour.Flood2  .flood.wt2.ml                 61212      61222      61232
labour.Flood2  .flood.wt3.ml                 61213      61223      61233
labour.Flood2  .pivot.wt1.ml      61111      61211      61221      61231
labour.Flood2  .pivot.wt2.ml      61112      61212      61222      61232
labour.Flood2  .pivot.wt3.ml      61113      61213      61223      61233
;
*
TABLE
resource_f(f,wt,r) farm level resource availability - units per farm per time
          labour    tractor
farm1.wt1     111        112
farm1.wt2     121        122
farm1.wt3     131        132
farm2.wt1     211        212
farm2.wt2     221        222
farm2.wt3     231        232
;
*
TABLE
alloc(f,con,t) volumetric water allocation to each farm - m3 per annum
              y1         y2         y3
farm1.1con1  1111       1112       1113
farm1.1con2  1121       1122       1123
farm2.1con1  2111       2112       2113
;
```

Each crop may use different quantities of resources depending on the production possibilities Table pg_to_p is used to link a specific production area with different production possibilities. From Table pg_to_p it is clear that the production area Dryland 1 can be utilised for dryland production or irrigation whereas production area flood 1 can be used for flood or centre pivot irrigation. Next, the crops that can be grown by a specific production possibility are given by Table c_to_p.

The size of the production areas are given by parameter areas whereas the number of hectares of specific production possibilites are given by Table cur_irri_ha. Zero hectares are specified for flood irrigation, because it is assumed that the decision to utilise flood irrigation is made every year. Thus, the decision to flood irrigate crops will be determined by the crop. The same assumption is made for cash crops and only the hectares of crops with growing periods that extend over one year are specified in Table cur_crops_ha.

In order to model replacement of crops and irrigation systems that will impact on resources used, the user needs to specify the number of years before an irrigation system (irri_cycle) or a crop (crop_cycle) is replaced. For the current situation it is also necessary to determine the number of years the crop has utilised the area (cur_crop_cycle) and the number of years an irrigation system has been utilised (cur_irri_cycle).

Although the multiperiod model is an annual model it allows for the specification of resource use on a finer timestep within the year utilising set wt. Table grow specifies the time periods within the year a specific crop will utilise soils. Table gir and res_use respectively give the amounts of gross irrigation water and other resources used by a specific crop in a specific time period over the lifespan of the crop. The availability of these resources that can be utilised by each farm are given in Table resource_f and Table alloc.

4.1.2.3 *Financial*

The skeleton model allows for different irrigation cost specifications depending on the water source, geographical area and production possibility. The irrigation cost from the last water source to the irrigation system is given in Table irri_cost and includes the cost to convey the water to the system (pumping) as well as the cost of applying the water in the field. Since the costs in Table irri-cost only include the last link, the pumping cost to fill on-farm storage dams is given in Table pump_cost. The water tariffs paid to the water user association is specified with Parameter tarrif and is defined for each water source. Other production costs excluding irrigation cost is specified in Table operation_cap. Income generated from cropping activities is calculated using information on crop yields (Table crop_yield) and product prices which may be different for each farm (Table prices).

To model irrigation expansion options the investment capital necessary to develop a specific production area is given in Table invest_cap while the salvage percentages of each system are specified with parameter salvage_perc.

Tables, overheads and living_cost are used to specify the overhead and living expenses of each farm.

The following economic parameters are necessary as inputs.

```
TABLE
irri_cost(ws,p) irrigation cost from water source to irrigation system - rand
per unit
               flood        pivot
teroff1                       312
teroff2          321          322
teroff3          331          332
primoff1                      112
primoff2         121          122
primoff3                      132
borehole1                     412
dam1                          512
;
*
```

```
TABLE
pump_cost(ws,dam) pumping cost from water source to dam - rand per unit
                         dam1
teroff1                  3151
;
*
PARAMETER
tarrif(ws) primarary water abstracting tarrif - rand per unit
/teroff1       310
 teroff2       320
 teroff3       330
 primoff1      110
 primoff2      120
 primoff3      130
 borehole1     410/
;
*
TABLE
invest_cap(pg,irri) investment capital to expand irrigation - rand per ha
              flood       pivot
dryland1       1000        2000
Pivot1                    12000
Pivot2                    22000
Pivot3                    32000
Pivot4                    42000
Flood1        51000       52000
Flood2        61000       62000
;
*
PARAMETER
salvage_perc(irri) percentage salvage at end of economic life - %
/flood         100
 pivot          20/
;
*
TABLE
prices(f,c) average product prices  - rand per unit
              cropA       cropB
farm1          1000        2000
farm2          1000        2000
;
*
TABLE
crop_yield(pg,p,m,c,t) average crop yields - units per ha
                                  Y1         Y2         Y3
dryland1.dry  .m1.cropA            3
dryland1.flood.m1.cropB            5          6          7
dryland1.pivot.m1.cropA            9
dryland1.pivot.m1.cropB            7          8          8
Pivot1  .pivot.m1.cropA            9
Pivot1  .pivot.m1.cropB            7          8          9
Pivot2  .pivot.m1.cropA            9
Pivot2  .pivot.m1.cropB            7          8          9
Pivot3  .pivot.m1.cropA            9
Pivot3  .pivot.m1.cropB            7          8          9
Pivot4  .pivot.m1.cropA            9
Pivot4  .pivot.m1.cropB            7          8          9
Flood1  .flood.m1.cropB            5          6          7
Flood2  .flood.m1.cropB            5          6          7
;
*
TABLE
operating_cap(pg,p,m,c,pt) operating capital - rand per ha
                                  y1         y2         y3
dryland1.pivot.m1.cropA          211
Pivot1  .pivot.m1.cropA         1211
Pivot2  .pivot.m1.cropA         2211
Pivot3  .pivot.m1.cropA         3211
Pivot4  .pivot.m1.cropA         4211
flood1  .pivot.m1.cropA         5211
flood2  .pivot.m1.cropA         6211
dryland1.pivot.m1.cropB          221        222        223
```

```
Pivot1  .pivot.m1.cropB          1221       1222       1223
Pivot2  .pivot.m1.cropB          2221       2222       2223
Pivot3  .pivot.m1.cropB          3221       3222       3223
Pivot4  .pivot.m1.cropB          4221       4222       4223
flood1  .pivot.m1.cropB          5221       5222       5223
flood2  .pivot.m1.cropB          6221       6222       6223
dryland1.flood.m1.cropB           221        222        223
flood1  .flood.m1.cropB          5221       5222       5223
flood2  .flood.m1.cropB          6221       6222       6223
;
*
TABLE
overheads(f,t) overhead expenses - rand per time period
          (y1*y3)
farm1      100000
farm2      200000
;
*
TABLE
living_cost(f,t) household expenses - rand per time period
          (y1*y3)
farm1       10000
farm2       20000
;
*
TABLE
max_operating(f,t) operating capital borrowing limit - rand per time period
          (y1*y3)
farm1       10000
farm2       20000
;
display max_operating;
*
TABLE
max_borrow(f,t) investment capital borrowing limit - rand per time period
          (y1*y4)
farm1       10000
farm2       20000
;
display max_borrow;
*
TABLE
borrow_threshold(f,t)  maximum borrowing limit - rand per time period
          (y1*y3)
farm1        1999
farm2        2999
;
*
TABLE
reali(f,l) real interest rates - % per time period
                         borrow_ope borrow_inv      invest_bank
farm1                            10         17                5
farm2                            10         17                5
;
*
TABLE
cap_aval(f,t) capital availability - rand per time period
               y1
farm1      314000
farm2      270100
;
*
SCALARS
df  discount factor - fraction per time period /0.07/
tax_rate marginal tax rate -fraction per time period /0.35/
;
```

Several limits are necessary to control the utilisation of capital funds. The maximum amount of operating capital that a farm may utilise as production credit is specified in `Table max_operating`. A threshold amount that each farm may borrow for irrigation investment

```
*
PARAMETER
taxdep(pg,irri,pt) depreciation tax deduction;
taxdep(pg,irri,pt)$(ord(pt)=1)= invest_cap(pg,irri)*0.5 ;
taxdep(pg,irri,pt)$(ord(pt)=2)= invest_cap(pg,irri)*0.3 ;
taxdep(pg,irri,pt)$(ord(pt)=3)= invest_cap(pg,irri)*0.2 ;
option taxdep :0:2:1; display taxdep;
*
PARAMETER
book_value(pg,irri,t) book value for irrigation investment;
book_value(pg,irri,t)
                    $(ord(t)<= irri_cycle(irri))
  =invest_cap(pg,irri)
     -(
       (invest_cap(pg,irri)-invest_cap(pg,irri)*salvage_perc(irri)/100)
                                   /
                    irri_cycle(irri)
       )*ord(t);
option book_value :0:2:1;display book_value;
*
PARAMETER
payment(f,*,t) payment schedule for R1 ;
SCALAR
Length_Long_term /3/;

payment(f,"total",t)$(ord(t) le Length_Long_term)
      =(
        (reali(f,"borrow_inv")/100)*((1+(reali(f,"borrow_inv")/100))
         **Length_Long_term)
        )
        /(((1 + (reali(f,"borrow_inv")/100))**Length_Long_term)-1);

payment(f,"outstanding","y1") = 1;
loop((f,t),
       payment(f,"interest","y1")
         = 1*(reali(f,"borrow_inv")/100);
       payment(f,"principal","y1")
         = payment(f,"total","y1")-payment(f,"interest","y1");
       payment(f,"outstanding","y1")
         = 1 - payment(f,"principal","y1");

       payment(f,"interest",t)$(ord(t) le Length_Long_term )
         = (payment(f,"outstanding",t-1))*(reali(f,"borrow_inv")/100);
       payment(f,"principal",t)$(ord(t) le Length_Long_term )
         = (payment(f,"total",t)-payment(f,"interest",t));
       payment(f,"outstanding",t)$(ord(t) le Length_Long_term )
         = (payment(f,"outstanding",t-1) - payment(f,"principal",t));
    );
option payment :4:2:1;display payment;
```

The first two parameters identify the years for which a specific irrigation system or crop will occupy the land. The book value of the irrigation system in each year of the irrigation system cycle is calculated using the straight line method. Parameter `taxdep (pg, irri, pt)` calculates the allowable deduction in taxable income using a tax depreciation schedule of 50% in year 1, 30% in year 2 and 20% in year 3. The interest and principal portion, as well as the outstanding balance of a loan with a payback period of 3 years, is calculated with parameter `payment (f, *, t)`. The * allows for the specification of the alternative components.

After the calculation of the new input parameter the following GAMS code is used to appropriately assign input data and newly calculated parameters to each year in the planning horizon.

purposes is specified with Parameter `threshold`. These values do not represent the maximum amount a farm may borrow, but the minimum amount that they may borrow irrespective of their growth in net worth or any outstanding capital. Larger borrowing capacity is determined through the model and is a function of the growth in net worth. The amount of startup capital available is specified with Pararmeter `cap_aval`.

The rates used to calculate tax and interest, and to discount future values to present values are given in `Table reali` and Scalars `df` and `tax_rate` respectively.

4.1.3 CALCULATION OF THE PROGRAMMING MATRIX INPUT PARAMETERS

A procedure is adopted whereby minimum input data manipulation and calculation of new parameters takes place during the matrix specification part of the GAMS code. Rather, the input parameters specified in the previous section are manipulated and new parameters calculated before the matrix is specified. The adopted procedure allows for better verification of the model since it is easier to detect problems with the data when compared to equations with data manipulations and calculations. Manipulation of data refers to the generation of new data tables which ensure that the timing of resource use, cash income generation and cash expenses of different activities over the planning horizon correspond to the actual values of previous decisions (see next section for example).

In the sections to follow a distinction is made between parameters that are associated with activities that will be optimised and those parameters that represent the current situation, as well as the calculation of terminal values.

4.1.3.1 Parameters associated with variables

The main result of the GAMS code that calculates the parameters for the programming matrix specification section is that the values are appropriately assigned to each year in the planning horizon.

Before the dlp parameters are determined, some new parameters are calculated using the user specified inputs from the previous section. The GAMS code to generate these parameters is given below.

```
PARAMETER
irri_occu(irri,pt) land occupation determined by irri cycle - years;
irri_occu(irri,pt)= 1$(ord(pt) < (irri_cycle(irri)+1));
display irri_occu;
*
PARAMETER
crop_occu(c,wt,pt) land occupation determined by irri cycle - years;
crop_occu(c,wt,pt)= grow(wt,c)$(ord(pt) < (crop_cycle(c)+1));
display crop_occu;
```

```
PARAMETER
dlp_gir(pg,p,wt,m,c,t,it) DLP - gross irrigation requirement;
dlp_gir(pg,irri,wt,m,c,t,it)
                          $(ord(it)>=1)
  =gir(pg,irri,wt,m,c,t-(ord(it)-1))
;
option dlp_gir :0:6:1;display dlp_gir;
*
PARAMETER
dlp_res_use(r,pg,p,wt,m,c,t,it) DLP - resource use;
dlp_res_use(r,pg,p,wt,m,c,t,it)
                                $(ord(it)>=1)
  =res_use(r,pg,p,wt,m,c,t-(ord(it)-1))
;
option dlp_res_use :0:7:1;display dlp_res_use;
*
PARAMETER
dlp_crop_occu(c,wt,t,it) DLP - irrigation system occupation;
dlp_crop_occu(c,wt,t,it)
                          $(ord(it)>=1)
  =crop_occu(c,wt,t-(ord(it)-1));
;
option dlp_crop_occu :0:3:1;display dlp_crop_occu;
*
PARAMETER
dlp_irri_occu(irri,t,it) DLP - irrigation system occupation;
dlp_irri_occu(irri,t,it)
                          $(ord(it)>=1)
  =irri_occu(irri,t-(ord(it)-1));
;
option dlp_irri_occu :0:2:1;display dlp_irri_occu;
*
PARAMETER
dlp_invest(pg,irri,t,it) DLP - investment capital;
dlp_invest(pg,irri,t,it)
                          $(ord(t)=ord(it))
  =invest_cap(pg,irri);
;
option dlp_invest :0:3:1;display dlp_invest;
*
PARAMETER
dlp_salvage(pg,p,t,it) DLP - salvage values;
dlp_salvage(pg,irri,t,it)
                            $(ord(t)=ord(it)+irri_cycle(irri)-1)
  =invest_cap(pg,irri)*salvage_perc(irri)/100;
;
option dlp_salvage :0:3:1;display dlp_salvage;
*
PARAMETER
dlp_prodincome(f,pg,p,m,c,t,it) DLP - production income;
dlp_prodincome(f,pg,p,m,c,t,it)
                            $(
                              ord(it)>=1
                              and
                              pg_to_f(pg,f)
                              )
  =prices(f,c)*crop_yield(pg,p,m,c,t-(ord(it)-1));
;
option dlp_prodincome :0:5:1;display dlp_prodincome;
*
PARAMETER
dlp_operating(pg,p,m,c,t,it) DLP - operating capital;
dlp_operating(pg,p,m,c,t,it)
                          $(ord(it)>=1)
  =operating_cap(pg,p,m,c,t-(ord(it)-1));
;
option dlp_operating :0:4:1;display dlp_operating;
*
PARAMETER
dlp_sys_networth(pg,irri,t,it) DLP - irrigation system net worth;
dlp_sys_networth(pg,irri,t,it)
                                $(ord(it)>=1)
```

```
  =book_value(pg,irri,t-(ord(it)-1));
option dlp_sys_networth :0:3:1; display dlp_sys_networth;
*
PARAMETER
dlp_taxdep(pg,irri,t,it) DLP - depreciation tax deduction;
dlp_taxdep(pg,irri,t,it)
                                $(ord(it)>=1)
  =taxdep(pg,irri,t-(ord(it)-1));
;
option dlp_taxdep :0:3:1;display dlp_taxdep;
*
PARAMETER
dlp_payment(f,*,t,it)
;
dlp_payment(f,"interest",t,it)
                                        $(ord(it)>=1)
  =payment(f,"interest",t-(ord(it)-1));
dlp_payment(f,"principal",t,it)
                                        $(ord(it)>=1)
  =payment(f,"principal",t-(ord(it)-1));
dlp_payment(f,"outstanding",t,it)
                                        $(ord(it)>=1)
  =payment(f,"outstanding",t-(ord(it)-1));
option dlp_payment :4:3:1; display dlp_payment;
```

To demonstrate the working of the GAMS code parameter `dlp_gir (pg, p, wt, c, t, it)` will be used. The GAMS code that generates parameter `dlp_gir (pg, p, wt, c, t, it)` uses parameter `gir (pg, p, wt, c, t)` which is used to specify the gross irrigation requirements for a specific within year time period `(wt)` over the crop's lifecycle `(t)` and assign it appropriately to each year in the planning horizon `(it)`. Part of the results of this manipulation is given below.

```
----     624 PARAMETER dlp_gir  DLP - gross irrigation requirement

                                          y1          y2      y3        y4

dryland1.flood.wt1.m1.cropB.y1          1211
dryland1.flood.wt1.m1.cropB.y2          1221        1211
dryland1.flood.wt1.m1.cropB.y3          1231        1221    1211
dryland1.flood.wt1.m1.cropB.y4                      1231    1221      1211
dryland1.flood.wt2.m1.cropB.y1          1212
dryland1.flood.wt2.m1.cropB.y2          1222        1212
dryland1.flood.wt2.m1.cropB.y3          1232        1222    1212
dryland1.flood.wt2.m1.cropB.y4                      1232    1222      1212
dryland1.flood.wt3.m1.cropB.y1          1213
dryland1.flood.wt3.m1.cropB.y2          1223        1213
dryland1.flood.wt3.m1.cropB.y3          1233        1223    1213
dryland1.flood.wt3.m1.cropB.y4                      1233    1223      1213
dryland1.pivot.wt1.m1.cropA.y1          2111
dryland1.pivot.wt1.m1.cropA.y2                      2111
dryland1.pivot.wt1.m1.cropA.y3                              2111
dryland1.pivot.wt1.m1.cropA.y4                                        2111
```

dryland1.pivot.wt1.m1.cropB.y1	2211			
dryland1.pivot.wt1.m1.cropB.y2	2221	2211		
dryland1.pivot.wt1.m1.cropB.y3	2231	2221	2211	
dryland1.pivot.wt1.m1.cropB.y4		2231	2221	2211
dryland1.pivot.wt2.m1.cropA.y1	2112			
dryland1.pivot.wt2.m1.cropA.y2		2112		
dryland1.pivot.wt2.m1.cropA.y3			2112	
dryland1.pivot.wt2.m1.cropA.y4				2112
dryland1.pivot.wt2.m1.cropB.y1	2212			
dryland1.pivot.wt2.m1.cropB.y2	2222	2212		
dryland1.pivot.wt2.m1.cropB.y3	2232	2222	2212	
dryland1.pivot.wt2.m1.cropB.y4		2232	2222	2212
dryland1.pivot.wt3.m1.cropA.y1	2113			
dryland1.pivot.wt3.m1.cropA.y2		2113		
dryland1.pivot.wt3.m1.cropA.y3			2113	
dryland1.pivot.wt3.m1.cropA.y4				2113
dryland1.pivot.wt3.m1.cropB.y1	2213			
dryland1.pivot.wt3.m1.cropB.y2	2223	2213		
dryland1.pivot.wt3.m1.cropB.y3	2233	2223	2213	
dryland1.pivot.wt3.m1.cropB.y4		2233	2223	2213

The columns represent the different years in the planning horizon when the crop is planted. The index Y_1 to Y_4 in the rows shows the timing of gross irrigation requirements. For instance, crop B has a crop cycle of 3 years which means that once it is established it will require water for 3 years (bold values). When crop B is established in Y_2 it will require water in Y_2 to Y_4 of the planning horizon with the water requirements of Y_2 corresponding with the gross irrigation requirement of the first production year. The table also shows that crop B will require water in each of the within time periods. Crop A, which is planted under pivot irrigation, has a crop cycle of one year and therefore requires water only in one year and all the within year time periods.

Other parameters that are calculated include land occupation by crops and irrigation systems, salvage values, production income, irrigation system net worth and the payment schedule when one Rand is borrowed in any given year.

Similar results are obtained when the other parameters are assigned to a specific year in the planning horizon and will not be discussed further. However, the results of the assignments are given in Appendix A for selected indices to reduce the amount of data.

4.1.3.2 Parameters associated with the current situation

All the programming matrix input-output parameters calculated in the previous section except `dlp_invest (pg, irri, t, it)` and `dlp_payment (f, *, t, it)` are used to calculate input parameters for the current situation. The code below is used to calculate the parameters associated with the current situation.

```
PARAMETER
dlp_cur_gir(pg,p,wt,m,c,t,it) DLP - current gross irrigation requirement;
dlp_cur_gir(pg,irri,wt,m,c,t,"y1")
                        $cur_crop_cycle(pg,c)
  =gir(pg,irri,wt,m,c,t+cur_crop_cycle(pg,c))
;
option dlp_cur_gir :0:5:1;display dlp_cur_gir;
*
PARAMETER
dlp_cur_res_use(r,pg,p,wt,m,c,t,it) DLP - current resource use;
dlp_cur_res_use(r,pg,p,wt,m,c,t,"y1")
                        $cur_crop_cycle(pg,c)
  =res_use(r,pg,p,wt,m,c,t+cur_crop_cycle(pg,c))
;
option dlp_cur_res_use :0:6:1;display dlp_cur_res_use;
*
PARAMETER
dlp_cur_crop_occu(pg,wt,c,t,it) DLP - current land occupation by crops
cur_crop_occu_flag(pg,c,t,it);
cur_crop_occu_flag(pg,c,t,it)
                  $(
                    ord(t)<= ord(it)+crop_cycle(c)-1-cur_crop_cycle(pg,c)
                    and
                    ord(t) >= ord(it)
                    and cur_crop_cycle(pg,c)
                    )
   =1;
option cur_crop_occu_flag :0:3:1;display cur_crop_occu_flag;
dlp_cur_crop_occu(pg,wt,c,t,it)
  =grow(wt,c)* cur_crop_occu_flag(pg,c,t,it);
option dlp_cur_crop_occu :0:4:1;display dlp_cur_crop_occu;
*
PARAMETER
dlp_cur_irri_occu(pg,irri,t,it) DLP - current irrigation system occupation;
dlp_cur_irri_occu(pg,irri,t,"y1")
                        $(ord(t)<=irri_cycle(irri)-cur_irri_cycle(pg,irri)
                          and pg_to_p(pg,irri)*cur_irri_cycle(pg,irri)  )
  =irri_occu(irri,t);
;
option dlp_cur_irri_occu :0:3:1;display dlp_cur_irri_occu;
*
PARAMETER
dlp_cur_salvage(pg,p,t,it) DLP - current salvage values;
dlp_cur_salvage(pg,irri,t,"y1")
                          $(
                            ord(t)=irri_cycle(irri)-cur_irri_cycle(pg,irri)
                            and
                            pg_to_p(pg,irri)*cur_irri_cycle(pg,irri)
                            )
  =invest_cap(pg,irri)*salvage_perc(irri)/100;
;
option dlp_cur_salvage :0:3:1;display dlp_salvage,dlp_cur_salvage;
*
PARAMETER
dlp_cur_prodincome(f,pg,p,m,c,t,it) DLP - current production income;
dlp_cur_prodincome(f,pg,p,m,c,t,"y1")
                        $(pg_to_f(pg,f)*pg_to_p(pg,p)*cur_crop_cycle(pg,c))
  =prices(f,c)*crop_yield(pg,p,m,c,t+cur_crop_cycle(pg,c));
;
option dlp_cur_prodincome :0:5:1;display dlp_cur_prodincome;
```

```
*
PARAMETER
dlp_cur_operating(pg,p,m,c,t,it) DLP - current operating capital;
dlp_cur_operating(pg,p,m,c,t,"y1")
                        $(pg_to_p(pg,p)*cur_crop_cycle(pg,c))
  =operating_cap(pg,p,m,c,t+cur_crop_cycle(pg,c));
;
option dlp_cur_operating :0:5:1;display dlp_cur_operating;
*
PARAMETER
dlp_cur_sys_networth(pg,irri,t,it) DLP - current irri system net worth;
dlp_cur_sys_networth(pg,irri,t,"y1")
                           $(
                             pg_to_p(pg,irri)*cur_irri_cycle(pg,irri)
                             )
  =dlp_sys_networth(pg,irri,t+cur_irri_cycle(pg,irri),"y1");
option dlp_cur_sys_networth :0:3:1; display dlp_cur_sys_networth;
*
PARAMETER
dlp_cur_taxdep(pg,irri,t,it) DLP - current depreciation deduction;
dlp_cur_taxdep(pg,irri,t,"y1")
                           $(
                             ord(t)>cur_irri_cycle(pg,irri)
                             and
                             pg_to_p(pg,irri)*cur_irri_cycle(pg,irri)
                             )
  =dlp_taxdep(pg,irri,t,"y1");
option dlp_cur_taxdep :0:3:1; display dlp_cur_taxdep;
```

The main result for all the calculations is that it alters the timing of the values in the rows of the parameters. To illustrate, the results of parameter dlp_cur_gir (pg, p, wt, c, t, it) are given below.

```
----724 PARAMETER dlp_cur_gir    DLP - current gross irrigation
requirement

INDEX 1 = pivot1

                              y1

pivot.wt1.m1.cropB.y1       12221
pivot.wt1.m1.cropB.y2       12231
pivot.wt2.m1.cropB.y1       12222
pivot.wt2.m1.cropB.y2       12232
pivot.wt3.m1.cropB.y1       12223
pivot.wt3.m1.cropB.y2       12233
```

Values are only calculated and reported for crop B since it is the only crop with a crop cycle longer than one year. Furthermore results are only generated for Y_1 in the planning horizon since the current situation is associated with Y_1 although it uses resources for a period in the future. Recall that a value of one is specified for pivot 1, crop B and a value of two for pivot 2, and crop B in Table cur_crop_cycle (pg, c). Thus, only the two remaining years in the crop cycle have a water requirement for crop B planted on pivot 1.

The water requirements assigned to Y_1 and Y_2 therefore correspond to the gross irrigation requirement of crop B in year 2 and 3 of its production period.

The results of the other parameters for the current situation are given in Appendix A.

4.1.4 TERMINAL VALUES

Terminal values are necessary to ensure that activities with cash flow streams past the planning horizon are not penalised during the optimisation of the problem. The procedure proposed by Rae (1970) is used to calculate the terminal values, which are the sum of the cash flow streams past the planning horizon discounted to the values of the last year of the planning horizon. An annuity is added to these values to comprise the terminal value for that specific activity.

In order to discount the values appropriately to the values of the final year in the planning horizon it is necessary to know how many years an activity extends past the horizon. The following GAMS code is used to determine the number of years past the planning horizon for the cropping activities, investments and loan payments.

```
PARAMETER
t_plus_crop(c,it) number of crop years past the planning horizon;
t_plus_crop(c,it)
                  $((crop_cycle(c)-card(t)+ ord(it)-1)>=0)
  = (crop_cycle(c)-card(t)+ ord(it)-1)
;
display t_plus_crop;
*
PARAMETER
t_plus_inv(p,it) number of investment years past the planning horizon;
t_plus_inv(irri,it)
                  $((irri_cycle(irri)-card(t)+ ord(it)-1)>=0)
  = (irri_cycle(irri)-card(t)+ ord(it)-1)
;
display t_plus_inv;
*
PARAMETER
t_plus_pay(it) number of payment years past the planning horizon;
t_plus_pay(it)
                  $((Length_Long_term-card(t)+ ord(it)-1)>=0)
  = (Length_Long_term-card(t)+ ord(it)-1)
;
display t_plus_pay;
```

The results of the calculations are shown below for the cropping activities. The results of the other parameters are given in Appendix A.

```
----815 PARAMETER t_plus_crop number of crop years past the planning
horizon

                y3          y4

cropB       1.000       2.000
```

The results indicate that the number of years past the planning horizon increases the longer you wait to establish crops with crop cycles that are longer than one period. No value is calculated for year 1 and year 2 because the crop cycle is completed within the planning horizon.

The following GAMS code calculates the sum of discounted money flows for gross margin associated with cropping activities, salvage values and tax deductions associated with investment activities and payments associated with loan activities.

```
PARAMETER
t_plus_crop_pv(f,pg,p,m,c,it) present value of crop gross margin;
t_plus_crop_pv(f,pg,p,m,c,it)
  =sum(t
         $(pg_to_f(pg,f)
           and
           ord(t) <= crop_cycle(c)
           and
          (ord(t) >  crop_cycle(c)- t_plus_crop(c,it))),
        (
         +dlp_prodincome(f,pg,p,m,c,t,"y1")
         -dlp_operating(pg,p,m,c,t,"y1")
         -sum((wt,pws)
                   $pg_to_ws(pg,pws),
              dlp_gir(pg,p,wt,m,c,t,"y1")*(irri_cost(pws,p)+tarrif(pws))
              )
         )
         /(1+df)**(ord(t)-(crop_cycle(c)-t_plus_crop(c,it)))
        )
;
option t_plus_crop_pv :0:5:1;display t_plus_crop_pv;
*
PARAMETER
t_plus_sal_pv(pg,p,it) present value of salvage;
t_plus_sal_pv(pg,irri,it)
  =sum(t
        $(ord(t) <= irri_cycle(irri)
          and
         (ord(t) >  irri_cycle(irri)- t_plus_inv(irri,it))),
        dlp_salvage(pg,irri,t,"y1")
                       /
        (1+df)**(ord(t)-(irri_cycle(irri)-t_plus_inv(irri,it)))
        )
;
option t_plus_sal_pv :0:2:1;display t_plus_sal_pv;
*
PARAMETER
t_plus_dep_pv(pg,p,it) present value of depreciation;
t_plus_dep_pv(pg,irri,it)
  =sum(t
        $(ord(t) <= irri_cycle(irri)
          and
         (ord(t) >  irri_cycle(irri)- t_plus_inv(irri,it))),
        dlp_taxdep(pg,irri,t,"y1")
                       /
        (1+df)**(ord(t)-(irri_cycle(irri)-t_plus_inv(irri,it)))
        )
;
option t_plus_dep_pv :0:2:1;display t_plus_dep_pv;
*
PARAMETER
t_plus_pay_pv(f,*,it) present value of payments;
t_plus_pay_pv(f,"interest",it)
  =sum(t
        $(ord(t) <= Length_Long_term
          and
```

```
          (ord(t) >  Length_Long_term- t_plus_pay(it))),
        dlp_payment(f,"interest",t,"y1")
        /(1+df)**(ord(t)-(Length_Long_term-t_plus_pay(it)))
        )
;
t_plus_pay_pv(f,"principal",it)
  =sum(t
         $(ord(t) <= Length_Long_term
           and
          (ord(t) >  Length_Long_term- t_plus_pay(it))),
        dlp_payment(f,"principal",t,"y1")
        /(1+df)**(ord(t)-(Length_Long_term-t_plus_pay(it)))
        )
;
option t_plus_pay_pv :0:2:1;display t_plus_pay_pv;
```

Parameter `t_plus_crop_pv (f, pg, p, c, it)` is calculated as the sum of production income minus the operating capital minus the irrigation cost. Irrigation cost is calculated by multiplying the gross irrigation requirement with the total irrigation cost. The assumption is made that all the irrigation water is applied from the primary water source to simplify the model. Thus, the option where water can be pumped into a dam does not form part of the calculations. The calculations of the other parameters are rather straightforward and will not be discussed further.

The last part of the GAMS code calculates the annuities associated with cropping, investment and loan payments. The annuities are then discounted to values of the final year in the planning horizon using the code below.

```
PARAMETER
annuity_crop(f,pg,p,m,c,it) after tax annuity of crop gross margin;
annuity_crop(f,pg,p,m,c,it)
  =sum(t
          $(ord(t) <= crop_cycle(c)
            and t_plus_crop(c,it)
            ),
        (
        +dlp_prodincome(f,pg,p,m,c,t,"y1")
        -dlp_operating(pg,p,m,c,t,"y1")
        -sum((wt,pws)
                    $pg_to_ws(pg,pws),
              dlp_gir(pg,p,wt,m,c,t,"y1")*(irri_cost(pws,p)+tarrif(pws))
              )
         )
          / (1+df)**(ord(t)-1))/(df*((1+df)**(t_plus_crop(c,it)+1))
        )
;
option annuity_crop :0:5:1;display annuity_crop;
*
PARAMETER
annuity_sal(pg,p,it) annuity of salvage;
annuity_sal(pg,irri,it)
  =sum(t
         $(ord(t) <= irri_cycle(irri)
           and t_plus_inv(irri,it)
           ),
        +dlp_salvage(pg,irri,t,"y1")
          / (1+df)**(ord(t)-1))/(df*((1+df)**(t_plus_inv(irri,it)+1))
        )
;
option annuity_sal :0:2:1;display annuity_sal;
*
PARAMETER
annuity_dep(pg,p,it) annuity of depreciation ;
annuity_dep(pg,irri,it)
```

```
  =sum(t
        $(ord(t) <= irri_cycle(irri)
          and t_plus_inv(irri,it)
         ),
       +dlp_taxdep(pg,irri,t,"y1")
        / (1+df)**(ord(t)-1))/(df*((1+df)**(t_plus_inv(irri,it)+1))
       )
;
option annuity_dep :0:2:1;display annuity_dep;
*
PARAMETER
annuity_pay(f,*,it) annuity of payment ;
annuity_pay(f,"interest",it)
  =sum(t
        $(ord(t) <= Length_Long_term
          and t_plus_pay(it)
          ),
       dlp_payment(f,"interest",t,"y1")
         / (1+df)**(ord(t)-1))/(df*((1+df)**(t_plus_pay(it)+1))
       )
;
annuity_pay(f,"principal",it)
  =sum(t
        $(ord(t) <= Length_Long_term
          and t_plus_pay(it)
          ),
       dlp_payment(f,"principal",t,"y1")
         / (1+df)**(ord(t)-1))/(df*((1+df)**(t_plus_pay(it)+1))
       )
;
option annuity_pay :0:2:1;display annuity_pay;
```

Next, the specification of the base optimisation model will be discussed.

4.1.5 BASE MODEL SPECIFICATION

The conversion is used whereby capital letters are used to represent the variables in the equation specification of the model that is used to generate the programming matrix.

4.1.5.1 Objective function

The objective of the base model is to maximise net cash flows in the final year of the planning horizon and the after tax terminal values for activities that extend beyond the planning horizon. The GAMS specification of the objective function is given below.

```
EQUATION
OBJ objective function - maximise growth in net worth;
OBJ..
   sum((f,it)
             $(ord(it)=card(it)),
             CASH_SURPLUS(f,it)
       )
  +sum((f,pg,p,m,c,it)
                        $pg_to_f(pg,f),
                    QCROP(pg,p,m,c,it)
                    *(t_plus_crop_pv(f,pg,p,m,c,it)+annuity_crop(f,pg,p,m,c,it))
                    *(1-tax_rate)
                    /(1+df)**card(it)
       )
  +sum((pg,irri,it),
                    IRRISYS(pg,irri,it)
```

```
                  *(t_plus_sal_pv(pg,irri,it)+annuity_sal(pg,irri,it))
                  *(1-tax_rate)
                  /(1+df)**card(it)
      )
  -sum((f,it),
              BORROW_INV(f,it)
              *(t_plus_pay_pv(f,"principal",it)+annuity_pay(f,"principal",it)
                +(t_plus_pay_pv(f,"interest",it)+annuity_pay(f,"interest",it)
                  *(1-tax_rate))
                )
              /(1+df)**card(it)
      )
  +sum((pg,irri,it),
                    IRRISYS(pg,irri,it)
                    *(t_plus_dep_pv(pg,irri,it)+annuity_dep(pg,irri,it))
                    *tax_rate
                    /(1+df)**card(it)
      )

  =E= z;
```

From the specification it is clear that terminal values are associated with cropping activities (`QCROP`), irrigation system investment decisions (`IRRISYS`) and financing of irrigation investment decisions (`BORROW_INV`). More specifically the objective function is calculated as the cash flow in the terminal time period plus after tax terminal values for gross margins and salvage income minus terminal after tax payments plus terminal tax savings due to the fact that capital investments are tax deductible.

4.1.5.2 *Cash surplus and taxable income*

The calculated cash surplus in each year for each farm is a function of all cash income and expenses associated with current and new activities and is calculated using the following GAMS code.

```
EQUATION
CALC_CASH(f,t) calculate cash surplus at the end of each year;
CALC_CASH(f,t)..
  +sum((pg,p,m,c,it)
                    $pg_to_f(pg,f),
                    QCROP(pg,p,m,c,it)
                    *dlp_prodincome(f,pg,p,m,c,t,it)/(1+df)**(ord(t)-1)
                   +cur_crops_ha(pg,p,m,c)
                    *dlp_cur_prodincome(f,pg,p,m,c,t,it)/(1+df)**(ord(t)-1)
      )
  +sum((pg,irri,it)
                     $pg_to_f(pg,f),
                     cur_irri_ha(pg,irri)
                     *dlp_cur_salvage(pg,irri,t,it)/(1+df)**(ord(t)-1)
                    +IRRISYS(pg,irri,it)
                     *dlp_salvage(pg,irri,t,it)/(1+df)**(ord(t)-1)
      )
  +(BANK(f,t)*(1+(reali(f,"invest_bank")/100))/((1+df)**1))
  -(overheads(f,t)/(1+df)**(ord(t)-1))
  - sum(it
         $(ord(it)le ord(t)),
      ((dlp_payment(f,"principal",t,it)+dlp_payment(f,"interest",t,it))
      *BORROW_INV(f,it))/(1+df)**(ord(t)-1)
      )
  -(OPERATING_LOAN(f,t)*(1 + (reali(f,"borrow_ope")/100))/(1+df)**1)

  - TAX_INCOME(f,t)*tax_rate
```

```
  -(living_cost(f,t)/(1+df)**(ord(t)-1))
  =E= CASH_SURPLUS(f,t)
;
```

Two aspects are noticeable from the above specification. Firstly, it includes production income from both current and new cropping activities as well as salvage income generated from current investment and new investments. Secondly, it seems as if the option of paying for operating cost and investments with own capital is not taken into account. However, the bank balance included in the specification is net of any money used to cover operating expenses or to finance irrigation system investment decisions with own capital.

The following GAMS code is used to calculate the taxable income in each year for each farm.

```
EQUATION
CALC_TAXINCOME(f,t) calculate taxable income in each year;
CALC_TAXINCOME(f,t)..

   sum((pg,p,m,c,it)
                   $pg_to_f(pg,f),
                   QCROP(pg,p,m,c,it)
                    * dlp_prodincome(f,pg,p,m,c,t,it)/(1+df)**(ord(t)-1)
                   -QCROP(pg,p,m,c,it)
                    *dlp_operating(pg,p,m,c,t,it)/(1+df)**(ord(t)-1)
                   +cur_crops_ha(pg,p,m,c)
                    *dlp_cur_prodincome(f,pg,p,m,c,t,it)/(1+df)**(ord(t)-1)
                   -cur_crops_ha(pg,p,m,c)
                    *dlp_cur_operating(pg,p,m,c,t,it)/(1+df)**(ord(t)-1)
      )
  -sum((ws,irri,wt)
                    $(f_to_ws(f,ws)
                      and
                      sum(pg,(pg_to_ws(pg,ws)*pg_to_p(pg,irri)))),
                    IRRIAP(ws,irri,wt,t)
                    *irri_cost(ws,irri)/(1+df)**(ord(t)-1)
      )
  -sum((pws,irri,wt)
                    $(f_to_ws(f,pws)
                      and
                      sum(pg,(pg_to_ws(pg,pws)*pg_to_p(pg,irri)))
                      ),
                    IRRIAP(pws,irri,wt,t)
                    *tarrif(pws)/(1+df)**(ord(t)-1)
      )
  -sum((dam,ws,wt)
                   $(f_to_ws(f,dam)*dam_to_ws(dam,ws)),
                   PUMPDAM(dam,ws,wt,t)
                   *(pump_cost(ws,dam)+tarrif(ws))/(1+df)**(ord(t)-1)
      )

  -sum((pg,irri,it)
                    $pg_to_f(pg,f),
                    cur_irri_ha(pg,irri)
                    *dlp_cur_taxdep(pg,irri,t,"y1")/(1+df)**(ord(t)-1)
                   +IRRISYS(pg,irri,it)
                    *dlp_taxdep(pg,irri,t,it)/(1+df)**(ord(t)-1)
      )
  -sum(it
         $(ord(it)le ord(t)),
         BORROW_INV(f,it)
         *dlp_payment(f,"interest",t,it)/(1+df)**(ord(t)-1)
      )
  -(OPERATING_LOAN(f,t)*((reali(f,"borrow_ope")/100))/(1+df)**1)
  -(overheads(f,t)/(1+df)**(ord(t)-1))
```

```
  +sum((pg,irri,it)
                   $pg_to_f(pg,f),
                   cur_irri_ha(pg,irri)
                   *dlp_cur_salvage(pg,irri,t,it)/(1+df)**(ord(t)-1)
                  +IRRISYS(pg,irri,it)
                   *dlp_salvage(pg,irri,t,it)/(1+df)**(ord(t)-1)
       )
  +(BANK(f,t)*((reali(f,"invest_bank")/100))/((1+df)**1))
  -(TAX_TRANS(f,t-1)/((1+df)**1))

  +TAX_TRANS(f,t)
  =E=  TAX_INCOME(f,t)
;
```

Taxable income is calculated while allowing for deductions of interest paid and tax depreciation of capital goods. A special feature of the taxable income calculation is that it can defer tax payments to future years if a negative taxable income is generated using variable `TAX_TRANS (f, e)`.

4.1.5.3 Financing operating cost and irrigation system investments

The following GAMS code control the financing options available in the skeleton model to finance operating cost and irrigation system investments.

```
EQUATION
 OPERATING_BAL(f,t) operating capital balance;
 OPERATING_BAL(f,t)..
   sum((pg,p,m,c,it)
                  $pg_to_f(pg,f),
                  QCROP(pg,p,m,c,it)
                  *dlp_operating(pg,p,m,c,t,it)/(1+df)**(ord(t)-1)
                 +cur_crops_ha(pg,p,m,c)
                  *dlp_cur_operating(pg,p,m,c,t,it)/(1+df)**(ord(t)-1)
       )
    -sum((ws,irri,wt)
                     $(f_to_ws(f,ws)
                       and
                       sum(pg,(pg_to_ws(pg,ws)*pg_to_p(pg,irri)))),
                      IRRIAP(ws,irri,wt,t)
                      *irri_cost(ws,irri)/(1+df)**(ord(t)-1)
          )
    -sum((pws,irri,wt)
                     $(f_to_ws(f,pws)
                       and
                       sum(pg,(pg_to_ws(pg,pws)*pg_to_p(pg,irri)))
                       ),
                      IRRIAP(pws,irri,wt,t)
                      *tarrif(pws)/(1+df)**(ord(t)-1)
          )
  +sum((dam,ws,wt)
                    $(f_to_ws(f,dam)*dam_to_ws(dam,ws)),
                    PUMPDAM(dam,ws,wt,t)
                    *(pump_cost(ws,dam)+tarrif(ws))/(1+df)**(ord(t)-1)
       )
  -OPERATING_CAPITAL(f,t)
  -OPERATING_LOAN(f,t)
  =L= 0;
*
EQUATION
 INVEST_BAL(f,t) investment capital balance for each farm;
 INVEST_BAL(f,t)..
   Sum((pg,irri,it)
```

```
                    $pg_to_f(pg,f),
                    IRRISYS(pg,irri,it)
                    *dlp_invest(pg,irri,t,it)/(1+df)**(ord(t)-1)
        )
  -INVEST_CAPITAL(f,t)
  -BORROW_INV(f,t)
  =L= 0;
*
EQUATION
 BANK_BAL(f,t) bank balance;
 BANK_BAL(f,t)..
   BANK(f,t)
  +OPERATING_CAPITAL(f,t)
  +INVEST_CAPITAL(f,t)
  -CASH_SURPLUS(f,t-1)
  =L= cap_aval(f,t)/(1+df)**(ord(t)-1);
*
EQUATION
OPERATING_MAX(f,t) maximum operating capital borrowing capacity;
OPERATING_MAX(f,t)..
   OPERATING_LOAN(f,t)
   =L=
   max_operating(f,t)/(1+df)**(ord(t)-1);
*
EQUATION
BORROWING_CAPACITY(f,t) maximum investment capital borrowing capacity;
BORROWING_CAPACITY(f,t)..
   BORROW_INV(f,t)
   =L=
   borrow_threshold(f,t)/(1+df)**(ord(t)-1)
  +sum((pg,irri,it)
                    $pg_to_f(pg,f),
                    IRRISYS(pg,irri,it)
                    *dlp_sys_networth(pg,irri,t-1,it)/(1+df)**(ord(t)-1)
                   +cur_irri_ha(pg,irri)
                    *dlp_cur_sys_networth(pg,irri,t,it)/(1+df)**(ord(t)-1)
        )
  -sum(it
          $(ord(it)le ord(t)),
          BORROW_INV(f,it-1)
          *dlp_payment(f,"outstanding",t,it)/(1+df)**(ord(t)-1)
        );
```

Equation `OPERATING_BAL(f,t )` shows that operating cost can be financed through a one-year operating loan (`OPERATING_LOAN(f, t)`) or operating capital (`OPERATING_CAPITAL (f, t)`) from the bank. Similarly investments can be financed through a borrowing activity (`BORROW_INV(f, t)`) or own capital (`INVEST_CAPITAL (f, t)`) from the bank.

Equation `BANK_BAL(f, t)` shows that operating capital and investment capital are supplied from the cash surplus from the previous year or any exogenous available capital (`cap_aval`).

The last two equations control the availability of production credit and borrowing capacity. The available amount of production credit is exogenously determined variables. More specifically the borrowing capacity is determined by a minimum amount that you may borrow plus the increase in the net worth of the farm as a result of irrigation investments minus any outstanding capital.

4.1.5.4 Irrigation system

The following two equations control irrigation system expansion opportunities and irrigated crop production possibilities.

```
EQUATION
 IRRI_POS(pg,irri,t) permission to grow crops with irrigation system;
 IRRI_POS(pg,irri,t)
                      $pg_to_p(pg,irri)..
  -cur_irri_ha(pg,irri)*dlp_cur_irri_occu(pg,irri,t,"y1")
  -sum(it,
         IRRISYS(pg,irri,it)
         *dlp_irri_occu(irri,t,it)
      )
  +sum((m,c,it)
            $(sum(wt,dlp_crop_occu(c,wt,t,it))
              and
              pg_to_p(pg,irri)*c_to_p(c,irri)),
            QCROP(pg,irri,m,c,it)
      )
   =L= 0 ;
*
EQUATION
 IRRI_MAX(pg,t) maximum irrigation expansion;
 IRRI_MAX(pg,t)..
   sum((irri,it)
                $pg_to_p(pg,irri),
                cur_irri_ha(pg,irri)*dlp_cur_irri_occu(pg,irri,t,it)
               +IRRISYS(pg,irri,it)*dlp_irri_occu(irri,t,it)
      )
   =L= areas(pg) ;
```

More specifically, equation `IRRI_POS (pg, irri, t)` restricts current and possible crop production with a specific irrigation technology to be less than the current and possible irrigation system expansion. Thus, the farmer needs to invest in an irrigation system first before any crop production using the specific irrigation technology is allowed. Equation `IRRI_MAX (pg, t)` restricts current irrigation system and investments in new irrigation systems to the area of the production area in each time period.

4.1.5.5 Resource use

The following two equations restrict the use of land and other resources to be less than the availability of such resources in a given time period.

```
EQUATION
 LANDMAX(pg,wt,t) maximum cultivated land in specific time period - ha;
 LANDMAX(pg,wt,t)..
   sum((p,m,c,it)
               $pg_to_p(pg,p),
               QCROP(pg,p,m,c,it)*dlp_crop_occu(c,wt,t,it)
              +cur_crops_ha(pg,p,m,c)*dlp_cur_crop_occu(pg,wt,c,t,it)
      )
   =L= areas(pg) ;
*
EQUATION
 RESUSE(f,r,wt,t) resource use by crops - units per time period wt;
 RESUSE(f,r,wt,t)..
   sum((pg,p,m,c,it)
```

```
                    $(pg_to_f(pg,f)*pg_to_p(pg,p)),
                    QCROP(pg,p,m,c,it)*dlp_res_use(r,pg,p,wt,m,c,t,it)
                   +cur_crops_ha(pg,p,m,c)*dlp_cur_res_use(r,pg,p,wt,m,c,t,it)
        )
   =L= resource_f(f,wt,r);
```

4.1.5.6 Irrigation water supply

Irrigation water supply will be discussed in two sections on-farm and off-farm. The following GAMS code controls the use of on-farm irrigation water use.

```
EQUATION
IRRIBALANCE(pg,irri,wt,t) irrigation system water supply balance - m3;
IRRIBALANCE(pg,irri,wt,t)..
   sum((c,m,it)
              $pg_to_p(pg,irri),
              QCROP(pg,irri,m,c,it)*dlp_gir(pg,irri,wt,m,c,t,it)
             +cur_crops_ha(pg,irri,m,c)*dlp_cur_gir(pg,irri,wt,m,c,t,it)
        )
  -sum(ws
         $(pg_to_ws(pg,ws)*pg_to_p(pg,irri)),
         IRRIAP(ws,irri,wt,t)
        )
   =L= 0;
*
EQUATION
 WS_CAP(ws,irri,wt,t) abstraction capacity from ws to irrigation field - m3
per time period wt;
 WS_CAP(ws,irri,wt,t)..
   sum((pg)
           $(pg_to_ws(pg,ws)*pg_to_p(pg,irri)),
           IRRIAP(ws,irri,wt,t)
        )
   =L= wscap(ws,irri);
*
EQUATION
 WSDAM_CAP(ws,dam,wt,t) abstraction capacity from ws to dam -m3 per time
period wt;
 WSDAM_CAP(ws,dam,wt,t)
                          $dam_to_ws(dam,ws)..
   PUMPDAM(dam,ws,wt,t) =L= damwscap(dam,ws);

*
EQUATION
DAMLEVEL(dam,wt,t) calculate dam level - m3 per time period wt;
*link dam level van een periode na die volgende behalwe vir eerste van
volgende jaar
DAMLEVEL(dam,wt,t)
                     $(not (ord(wt)=1 and ord(t)>1))..
  -sum((irri,pg)
                 $(pg_to_ws(pg,dam)*pg_to_p(pg,irri)),
                 IRRIAP(dam,irri,wt,t)
        )
  +sum(ws
         $dam_to_ws(dam,ws),
         PUMPDAM(dam,ws,wt,t)
        )
  +DLEVEL(dam,wt-1,t)
   =E= DLEVEL(dam,wt,t);
*
EQUATION
DAMLEVEL1(dam,wt,t) calculate dam level - m3 per time period wt;
*link dam level van een jaar na die volgende
DAMLEVEL1(dam,wt,t)
                     $((ord(wt)=1 and ord(t)>1))..
  -sum((irri,pg)
                 $(pg_to_ws(pg,dam)*pg_to_p(pg,irri)),
```

```
                 IRRIAP(dam,irri,wt,t)
          )
   +sum(ws
         $dam_to_ws(dam,ws),
         PUMPDAM(dam,ws,wt,t)
         )
   +DLEVEL(dam,wt+(card(wt)-1),t-1)
    =E= DLEVEL(dam,wt,t);
*
EQUATION
DAM_CAP(dam,wt,t) maximum dam capacity - m3 per time period wt;
DAM_CAP(dam,wt,t)..
   DLEVEL(dam,wt,t) =L= damcap(dam);
```

Equation `IRRI_BALANCE (pg, irri, wt, t)` shows that the model allows water to be applied to current and newly established .... from any water source `(ws)` which includes offtakes from conveyance, on-farm storage dams and boreholes. The operator is used to ensure that the water source possibilities are the same as those specified by the input parameters `pg_to_ws (pg, ws)` and `pg_to_p (pg, irri)`.

Equation `WS_CAP (ws, irri, wt, t)` restricts the amount of water applied to the supply capacity of the irrigation conveyance system combination. The amount of water pumped to the dam is restricted by the capacity of the conveyance system from the water source to the dam with Equation `WSDAM_CAP (ws, dam, wt, t)`.

Three equations are necessary to model the dam balance correctly. Equation `DAMLEVEL (dam, wt, t)` links the dam level of the previous within year time period `(wt)` to the next, but ignores the link from one year to another. The last mentioned link is modelled through equation `DAMLEVEL1 (dam, wt, t)`. More specifically the dam level in any given time period is a function of water pumped into the dam, water applied and the previous time periods water level. Equation `DAM_CAP (dam, wt, t)` restricts the dam level to be less than the capacity of the dam.

Off-farm supply is modelled with three equations ensuring that a farmer does not use more water than his allocation from the primary water conveyance system and that the off-farm conveyance has the capacity to supply the water. The GAMS code follows.

```
EQUATION
CALC_CON(con,wt,t) irrigation water demand from conveyance - m3;
CALC_CON(con,wt,t)..
   sum((off,irri)
                 $(sum(pg,
                        con_to_off(con,off)*pg_to_ws(pg,off)*pg_to_p(pg,irri))),
                 IRRIAP(off,irri,wt,t)
         )
  +sum((off,dam)
                $(dam_to_ws(dam,off)*con_to_off(con,off)),
                PUMPDAM(dam,off,wt,t)
         )
   =E= QCON(con,wt,t);
```

```
*
EQUATION
 CON_CAP(con,wt,t) maximum conveyance capacities - m3;
 CON_CAP(con,wt,t)..
   QCON(con,wt,t)
*link primary conveyance to other conveyance
  +sum(con1$(sum(con2,con_to_con(con,con1,con2))),QCON(con1,wt,t))
  +sum(con2$(sum(con1,con_to_con(con,con1,con2))),QCON(con2,wt,t))

*link secondary conveyance to tertiary conveyance
  +sum(con2$(sum(con1,con_to_con(con1,con,con2))),QCON(con2,wt,t))

   =L= concap(con);
*
EQUATION
 ALLOCATION(f,con,t) water allocation constraint - m3 per annum;
 ALLOCATION(f,con,t)
                  $prim(con)..
   sum((off,irri,wt)
                    $sum(pg,
                           con_to_off(con,off)*pg_to_f(pg,f)
                           *pg_to_ws(pg,off)*pg_to_p(pg,irri)
                         ),
                   IRRIAP(off,irri,wt,t)
      )
  +sum((off,dam,wt)
                $sum(pg,
                       dam_to_ws(dam,off)*con_to_off(con,off)
                       *pg_to_f(pg,f)*pg_to_ws(pg,off)
                     ),
                PUMPDAM(dam,off,wt,t)
      )
  +sum((con1,off,irri,wt)
                          $(sum(con2,con_to_con(con,con1,con2))
                            and
                            sum(pg,pg_to_f(pg,f)*pg_to_ws(pg,off)
                               *pg_to_p(pg,irri))
                           ),
                          IRRIAP(off,irri,wt,t)*con_to_off(con1,off)
      )
  +sum((con1,off,dam,wt)
                      $(sum(con2,con_to_con(con,con1,con2))
                        and
                        sum(pg,dam_to_ws(dam,off)
                             *pg_to_f(pg,f)*pg_to_ws(pg,off))
                       ),
                      PUMPDAM(dam,off,wt,t)
      )

  +sum((con2,off,irri,wt)
                          $(sum(con1,con_to_con(con,con1,con2))
                            and
                            sum(pg,pg_to_f(pg,f)*pg_to_ws(pg,off)
                               *pg_to_p(pg,irri))
                           ),
                          IRRIAP(off,irri,wt,t)*con_to_off(con2,off)
      )
  +sum((con2,off,dam,wt)
                         $(sum(con1,con_to_con(con,con1,con2))
                           and
                           sum(pg,dam_to_ws(dam,off)
                               *pg_to_f(pg,f)*pg_to_ws(pg,off))
                          ),
                         PUMPDAM(dam,off,wt,t)
      )
   =L= alloc(f,con,t);
```

`ALLOCATION (f, con, t)` is used to ensure that the amount of water abstracted, (irrigation water applied and pumped to dam) is less than the amount allocated to a farmer. Since water is allocated from the primary conveyance system it is necessary to link each farmer's offtakes to a primary conveyance. This is done with a conditional sum using the input parameters specified by the user. More specifically the parameters are `con_to_off (con, off)`, `pg_to_f (pg, f)`, `pg_to_ws (pg, off)` and `pg_to_p (pg, irri)`.

`CALC_CON (con, wt, t)` is used to calculate the amount of water abstracted from a specific level of conveyance (primary, secondary and tertiary). A conditional summation is used to ensure that cumulative amounts of water abstracted as the order of the conveyance system increases is less than the capacity of the conveyance system. For instance the second order conveyance system also needs to be able to convey water demanded in the linked third-order conveyance system.

4.1.6 RISK SKELETON MODEL

4.1.6.1 Data input

A quadratic risk programming formulation is used to incorporate risk into the skeleton model. In order to calculate the variance-covariance matrix the following two parameters must be specified.

```
TABLE
correl(t,st,it,st1) intra and intertemporal correlation matrix
          Y1.cropA   Y1.cropB   Y2.cropA   Y2.cropB   Y3.cropA   Y3.cropB

Y1.cropA         1       -0.7        0.1
Y1.cropB      -0.7          1                  -0.2
Y2.cropA       0.1                     1       -0.7        0.1
Y2.cropB                 -0.2       -0.7          1                   0.2
Y3.cropA                             0.1                     1       -0.7
Y3.cropB                                       -0.2       -0.7          1
;
*
```

```
TABLE
stdev(pg,p,m,st) standard deviation
                           cropA      cropB
dryland1.dry   .m1            10
dryland1.flood.m1                       120
dryland1.pivot.m1             30       1130
Pivot1   .pivot.m1           100       1100
Pivot2   .pivot.m1           200       1200
Pivot3   .pivot.m1           300       1300
Pivot4   .pivot.m1           400       1400
Flood1   .pivot.m1           500       1500
Flood2   .pivot.m1           600       1600
Flood1   .flood.m1                     1700
Flood2   .flood.m1                     1800
;
```

The intra- and intertemporal correlation matrix between different crops is used to calculate the variance–covariance matrix. By specifying the correlation matrix, the user is allowed to determine the intertemporal correlation. `Table correl` portrays an example where only first order auto-correlation is taken into account (Richardson, Klose and Gray, 2000). The intertemporal correlation coefficients are calculated using the time series of gross margins lagged one year. Furthermore the correlation must be specified for crops only. Thus the assumption is made that the correlation between management alternatives will stay the same although standard deviations may be changed. `Table stdev` gives the standard deviations of cash crop gross margins.

4.1.6.2 *Calculation of programming matrix input parameters*

The only parameter that is calculated for the risk specifications of the programming model is the variance-covariance matrix. The following GAMS code calculates the parameter by multiplying the correlation matrix with the standard deviations.

```
PARAMETER
var_covar(pg,p,m,t,c,pg1,p1,m1,it,c1) covariance matrix;
var_covar(pg,p,m,t,st,pg1,p1,m1,it,st1)
  = correl(t,st,it,st1)
    *stdev(pg,p,m,st)
    *stdev(pg1,p1,m1,st1);
options var_covar:2:5:5;display var_covar;
```

4.1.6.3 *Risk model specification*

The objective function of the quadratic risk programming model is to minimise total variance subject to a minimum net present value of net worth.

```
EQUATION
MINVARCOV minimise discounted total variance;
MINVARCOV..
SUM((pg,p,m,t,st,pg1,p1,m1,it,st1)
                                        $(   SAMEAS (pg,pg1)
                                         and SAMEAS (p,p1)
                                         and SAMEAS (m,m1)
                                         and SAMEAS (t,it)
                                         and SAMEAS (st,st1)
                                           ),
                                        (QCROP(pg,p,m,st,it)
                                        *QCROP(pg,p,m,st,it)
                                        *var_covar(pg,p,m,t,st,pg1,p1,m1,it,st1)
                                         )/(((1+df)**(ORD(T)-1))**2)
    )
+SUM((pg,p,m,t,st,pg1,p1,m1,it,st1)
                                        $(  not SAMEAS (pg,pg1)
                                         or not SAMEAS (p,p1)
                                         or not SAMEAS (m,m1)
                                         or not SAMEAS (t,it)
                                         or not SAMEAS (st,st1)
                                           ),
                                        (QCROP(pg,p,m,st,t)
                                        *QCROP(pg1,p1,m1,st1,it)
                                        *var_covar(pg,p,m,t,st,pg1,p1,m1,it,st1)
                                         )/((1+df)**(ORD(T)+ORD(it)-2))
      )
  =E= VARIANCE;
*
EQUATION
TARGET target npv that should be obtained with minimum variance;
TARGET..
   Z
  =E= target_npv
```

The variance-covariance matrix is discounted using procedures of Bussey (1978). Equation TARGET is used to constrain the objective function value (Z) of the base model to be equal to the specified target net present value.

4.2 APPLICATION OF THE SKELETON DYNAMIC LINEAR PROGRAMMING MODEL IN VAALHARTS

To demonstrate the applicability of the model it was applied to a section of the canal distribution network in Vaalharts. Field visits, discussions with water managers, farmers and agricultural advisors, secondary data from Badenhorst (2003) and representative farms compiled by Louw (2002) served as the main sources of information to set up the model.

4.2.1 DOMAIN OF THE APPLICATION AND WATER SUPPLY

Figure 4.3 gives a schematic representation of the canal distribution network of one of the feeder canals in Vaalharts as well as production possibilities. In this specific case the Northern canal supply feeder canal five of water while feeder canal five supplies several tertiary or community canals with water. In general each tertiary canal consists of six 25 ha plots, each with its own sluice. The capacity of the tertiary canal is generally sufficient to supply two plots simultaneously with water (2×150 m^3 per hour). The domain (size) of the model was reduced by lumping together, along a specific tertiary canal plots that belong to the same owner. In order to demonstrate the applicability of the model the water distribution of tertiary canal 5C was optimised. Canal 5C consists of two three plot production units and corresponds to a medium size representative farm (1B4_3B4 and 4B4_6B4). The first production unit is under flood irrigation while the second has a centre pivot of 35 ha and 41 ha of flood irrigation. The second farm also has on-farm storage facilities with a capacity of 7 200 m^3.

Irrigation can take place directly from the tertiary canals or from the on-farm storage dams. The model is set up for 15 years with resource use accounted for on a weekly basis.

4.2.2 RESOURCE AVAILABILITY AND USE

It is assumed that the two production units are suited for the cultivation of maize, wheat, groundnuts, lucerne and pecan nuts. Maize and groundnuts compete for available resources during the summer while lucerne and pecan nuts take soil out of production for 6 and 15 years respectively once it is established. Pecan nuts are flood irrigated whereas the other crops can either be irrigated with flood or centre pivot irrigation. The assumption is made that a pivot will last for 15 years and that the farmer was operating the system for the last three years.

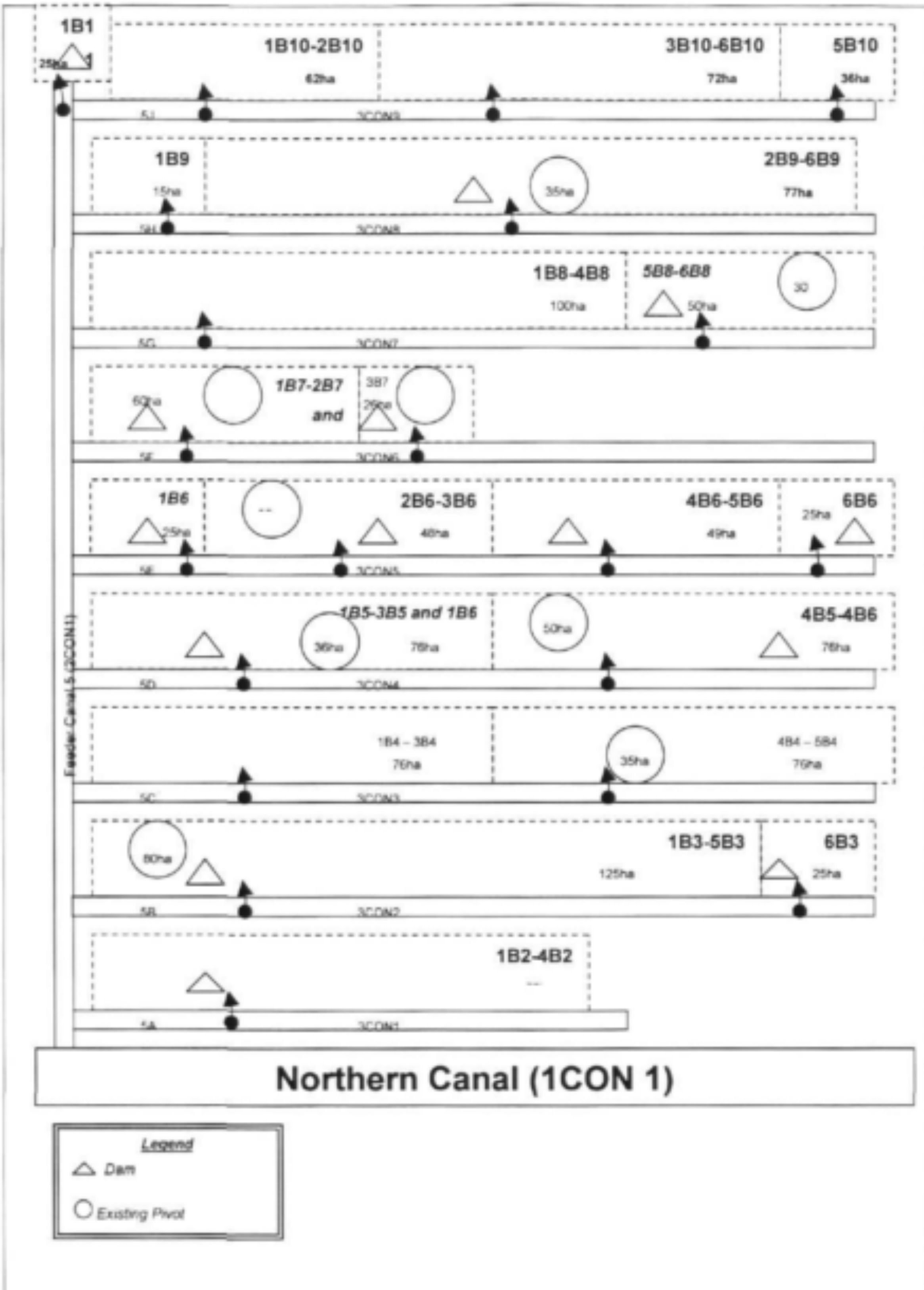


Figure 4.3: Schematic representation of the water distribution network of one of the feeder canals in Vaalharts.

The dominant crops grown in the area are maize, groundnuts, wheat, pecan nuts and lucerne. Each farm is allocated 914 mm per ha per annum which results in a total water allocation of 69 464 mm of water. Economic theory requires several irrigation activities for each crop to optimise water use between multiple crops. However, in this research only one full irrigation schedule was used for crops irrigated with flood irrigation and the long term crops. A modified SAPWAT was used to estimate crop water requirements for 256 different irrigation schedules for pivot irrigation and one irrigation schedule for flood irrigation systems. The procedures used to estimate gross irrigation requirements under conditions of limited water supply and the resulting crop yields are discussed in Section 4.3.

The assumption was made that available tractor and labour hours will not influence the optimal solution to reduce the size of the programming matrix in the presence of the alternative irrigation schedules necessary to model water allocation between multiple crops.

4.2.3 Financial

Representative farms compiled by Louw (2002) are used as the basis for the financial parameters. Each farm within the canal distribution network is allocated to a specific representative farm based on the size of the farming operations. Enterprise budgets from GWK and SENWES were used to calculate operating capital. Centre pivot irrigation system designs from SENWES for a representative 1-plot and 2-plot situation were used to estimate investment cost and irrigation cost of applying water.

The input file used in this research is given in Appendix E.

4.3 ESTIMATING GROSS IRRIGATION REQUIREMENTS AND CROP YIELDS WITH SAPWAT UNDER LIMITED WATER SUPPLY CONDITIONS

SAPWAT was developed with the aim of calculating crop water requirements under conditions of unlimited water supply conditions. Although an indication is given when the crop will undergo water stress due to limited water supplies no crop yields are estimated. The main objective of this section is to describe the procedures used to increase efficiencies under deficit irrigation regimes and to describe the procedures used to estimate crop yields.

4.3.1 Incorporating Coefficient of Uniformity

In order to determine crop water requirements for deficit irrigation schedules the SAPWAT procedures were augmented with procedures developed by Li (1998) to calculate gross irrigation requirements taking the coefficient of uniformity (CU) into account. Figure 4.4 will be used to describe the procedures in more detail.

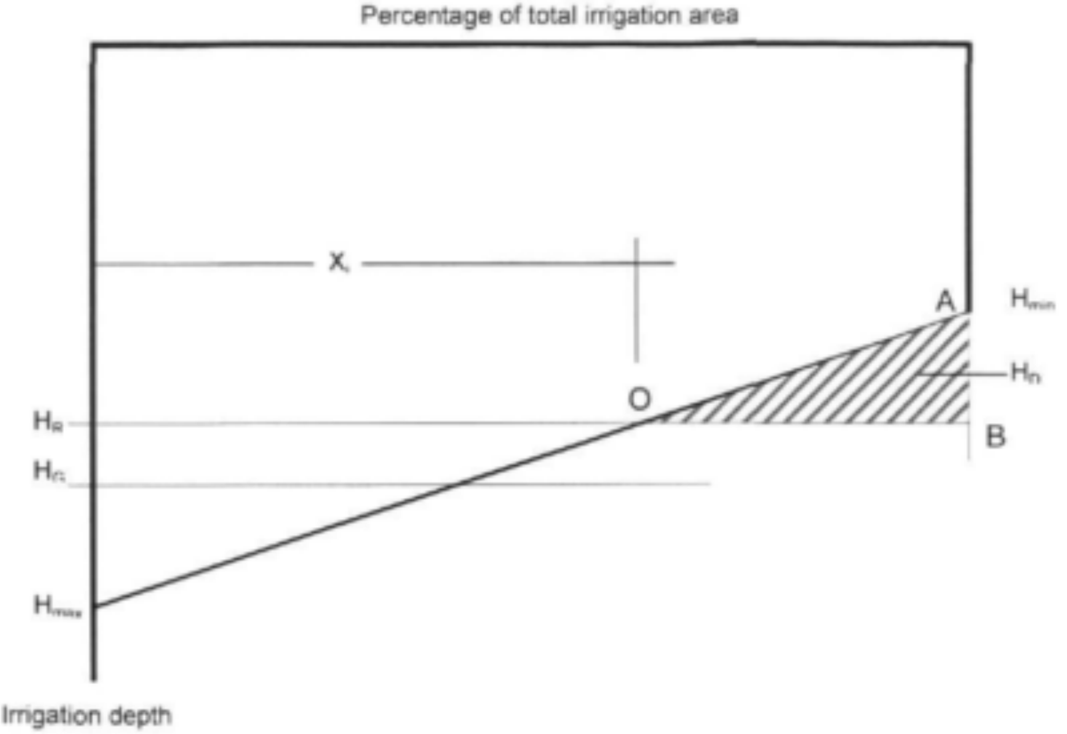


Figure 4.4: Probability distribution of irrigation depths assuming a uniform distribution. Symbols defined in text.

Let us assume the irrigator needs to compensate for a soil water depletion or required depth *(H_R)*. In normal practice one will apply gross irrigation depth *(H_G)*. Due to non-uniform applications some portion of the field will receive more water and some less with an average deficit of H_D. Assuming a uniform distribution, an irrigation system will apply water uniformly between a minimum *(H_{min})* and maximum *(H_{max})* level. The result is that $H_R\ O\ H_{max}$ represents areas where too much water is applied and $B\ O\ H_{min}$ or H_D areas where too little water is applied.

A deficit coefficient *(C_D)* which gives the percentage deficit is defined as: $C_D = \dfrac{H_D}{H_r}$

The relationship between CU, H_{max} and H_G is given by: $$CU = 1 - \frac{H_{max} - H_G}{2H_G} \qquad \text{(A)}$$

The average amount of water applied is calculated as: $$H_G = \frac{1}{2}\left(H_{max} + H_{min}\right) \qquad \text{(B)}$$

If one knows the CU and H_G it is possible to calculate H_{max} and H_{min} using Equations A and B. The relationship between C_D and CU, H_r and H_D is given by:

$$C_D = \frac{(1 - 2CU + H_R / H_G)[1 - H_G / H_R(2CU - 1)]}{8 - 8CU} \, for H_{max} \geq H_R \qquad \text{(C)}$$

$$C_D = 1 - \frac{H_G}{H_R} \, for H_{max} < H_R \qquad \text{(D)}$$

From Figure 4.4 it is clear that if H_{max} is greater than H_R loss will be minimised. The average amount (H_A) of water that contributes to H_R is calculated as: $H_A = H_R - H_D \cdot H_R$

H_A is taken as the net irrigation amount taken up in the root zone of the SAPWAT water budget, whereas the rest (H_D x H_R) enters the SAPWAT water budget as below the root zone.

4.3.2 CROP YIELD ESTIMATION

SAPWAT calculates maximum evapotranspiration (ET_m) and actual evapotranspiration (ET_a) during each day of the growing season.

Crop yield was calculated with the use crop yield response factors (*ky*) which relate relative yield decrease (*1-Ya/Ym*) to relative evapotranspiration deficit (*1-ETa/ETm*). More specifically the Stewart multiplicative (De Jager, 1994) relative evapotranspiration formula was used to calculate crop yield taking the effect of water deficits in different crop growth stages into account:

$$Ya = Ym \times \prod_{g=1}^{4} \left(1 - ky_g \left(1 - \left(\frac{\sum_{t=1}^{m} ETa_{tg}}{\sum_{t=1}^{m} ETm_{tg}} \right) \right) \right) \qquad (1)$$

with:

Ya	actual crop yield (ton/ha)
Ym	maximum potential crop yield (ton/ha)
ETa	actual evapotranspiration (mm.ha)
ETm	maximum potential evapotranspiration (mm.ha)
ky	crop yield response factor
g	growth stages
m	length of crop growth stage in days

Crop yields and water use on a weekly basis were estimated for 256 different combinations of water stress in each of the crop growth stages. The irrigation is triggered whenever the specified deficit was reached. Variability of the crop yields was estimated for each of the three states of nature included in SAPWAT.

4.4 CALCULATION OF RISK PARAMETERS

A separate GAMS model was developed to generate the necessary variance-covariance matrix or deviation matrix for the Skeleton DLP model. These matrices are calculated from appropriately correlated sequences of simulated crop yields over a period of 15 years for 100 states of nature. Deterministic constant prices were assumed.

Procedures developed by Richardson, Klose and Gray (2000) was used to simulate the crop yields from intra- and intertemporal correlation matrices. Since SAPWAT only includes normal, severe drought and favourable weather sets the triangle distribution is used to simulate the sequences.

The cumulative probability distribution ($F_{(x)}$) of the triangular distribution is completely specified by the minimum (a), maximum (c) and the mode (b) (Hardaker, Huirne and Anderson, 1997). Through the use of the inverse transform method it is possible to simulate random values of x for any uniformly distributed value (U) between zero and one. More specifically the inverse transform function of the triangular distribution is given by:

$$x = a + \left(u(c-a)(b-a)\right)^{0,5} \; for O \le U \le (b-a)/(c-a)$$
$$x = c - \left((1-u)(c-a)(c-b)\right)^{0,5} \; for (b-a)/(c-a) < U \le 1$$

Next the procedure used to correlate U intra- and intertemporally will be discussed using Richardson (2004).

First independent standard normal deviates (ISND) equal to the number of random entities multiplied by the number of years multiplied by the number of iterations is generated. These ISND are then correlated for a specific year by multiplying the matrix of ISND with the Cholesky decomposed correlation matrix. The Cholesky matrix for the lower triangle of the correlation matrix is obtained with the following equations (Dagpunar, 1988: 157):

$$C_{ii} = \sqrt{\left(V_{ii} - \sum_{m=1}^{i-1} C_{im}^2\right)}$$
$$C_{ij} = \left(V_{ij} - \sum_{m=1}^{i-1} C_{im} C_{jm}\right) / C_{ii} \, forj7i$$

When the Cholesky matrix is multiplied with its transpose, one should obtain the correlation matrix ($CC^T = V$). The CSND are adjusted to reflect intertemporal correlation matrix. The intertemporal correlation matrix is established assuming no second order correlation and is calculated by correlating the input data with a one-year lag. Once the CSND are adjusted for intertemporal correlation it is made uniform by integrating the area under the normal distribution. The error *f* function in GAMS is used to do the integration. The GAMS code used to simulate sequences of appropriately correlated gross margins is shown in Appendix A.

A major difference between the employed GAMS code and the procedures used by Richardson (2004) is that you have to generate ISND for all the iterations before correlating them. Furthermore the GAMS code calculates the lower triangle Cholesky matrix whereas Richardson (2004) calculates the upper triangle. Working with the lower triangle is more efficient since one does not need to reverse the order of the years of simulation.

The simulated sequences can be used to calculate the intertemporal variance-covariance matrix for use with the quadratic programming model or the deviations from the mean for use with MOTAD.

CHAPTER 5

RESULTS AND CONCLUSIONS

The main objective of this chapter is to optimise water use in the Vaalharts area taking risk into account. Due to the interactions between years, and the number of deficit irrigation schedules included and currently available and solvers such as MINOS and CONOPT it was not practically feasible to solve the total distribution network given in Figure 4.2.[1] To demonstrate the use of the model only tertiary canal 5C was optimised. Canal 5C consists of two farmers each having 76 ha of land. The main difference is that farm 2 has already adopted centre pivot irrigation on 35 ha and has planted pecan nuts on 35 ha. The model is solved within a single decision-maker framework.

5.1 DEFINING ALTERNATIVE SCENARIOS

In order to facilitate discussion of the results obtained through the application of the skeleton model the naming of the alternative scenarios will be done first.

RO	risk not taken into account
C1	current situation where farm 1 (f1) only has 76 ha of flood irrigation and farm 2 (f2) has a 35 ha pivot with 35 ha of pecan nuts.
C2	both farms have only flood irrigation without the possibility of investing in centre pivot irrigation
C3	both farms have only pivot irrigation
C9	farms may use either flood or centre pivot irrigation
NC9	same as C9, however, the scenario does not allow for the expansion into long-term crops (lucerne and pecan nuts)
W1	hundred per cent of water allocation
WO8	eighty per cent of water allocation
F1	farm 1
F2	farm 2

[1] Commercially available solvers such as CPLEX solves such large complex models.

5.2 RE-ALLOCATION OF WATER WITHOUT RISK

In this section the economic tradeoffs, when the total amount of water allocated to a specific farm are reduced uniformly across all years, are quantified without taking risk into account. Results are presented for both the total canal (Figure 5.1) and individual farms (Figure 5.2).

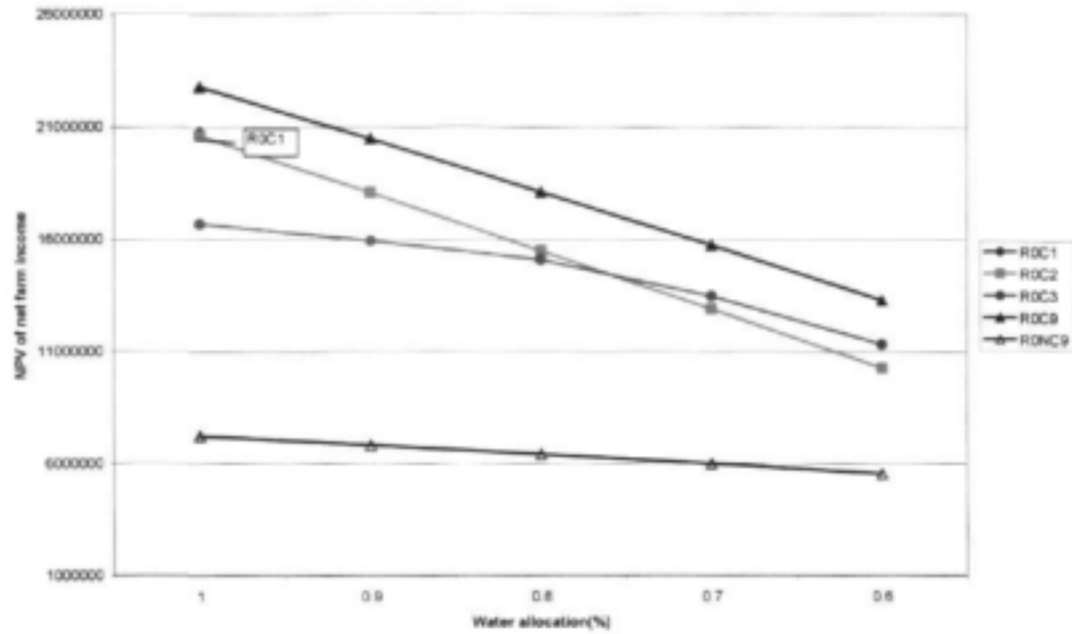


Figure 5.1: Economic tradeoffs under uniform water re-allocation situations at canal level.

With Scenario ROC1 no tradeoff is modelled. The implication of using a single decision-maker framework to optimise water use for the total area is that if one farm is infeasible, the total model will be infeasible. In this case F2 is infeasible. At lower levels of water availability, not enough cash crops can be grown to supply the necessary cash flow to sustain the farm while the pecan nuts (year 4 of production) come into production.

The highest net present values are obtained with Scenario ROC9 where the model determines the optimal mix of cash crops, long-term crops and irrigation investment decision given available starting capital.

The impact of the long-term crops on the results can be seen if Scenarios ROC2, ROC3 and RONC9 are compared. Scenario ROC2 has the highest NPV if more than 80% of the original water allocation is available. This is mainly due to the phased inclusion of pecan nuts into the model. However, when less than 80% of the water is available, Scenario ROC3 yields the best results. The slope of Scenario ROC3 is flatter than that of Scenario ROC2 indicating that the

NPV is not reduced that much as water availability is reduced. It should be remembered that deficit irrigation strategies are only allowed with centre pivots. Thus, Scenario ROC3 has much more manoeuvrability when water allocation is reduced compared to flood irrigation with pecan nuts. Scenario RONC9 has the best potential to handle water allocation reductions. However, the total NPV is much less than the other scenario since it does not include higher valued long-term crops.

The farm level tradeoff curves shown in Figure 5.2 are very similar to those of the total canal. Furthermore, very few differences are observed between the alternative scenarios with the exception of Scenario ROC1 where a significant difference is observed. The difference between the two farms is attributed to the specification of the initial situation. Farm 2 has 35 ha of pecan nuts in 4 years of production with little cash reserves. The delayed income of the pecan nuts impacts severely on cash flows resulting in a lower NPV.

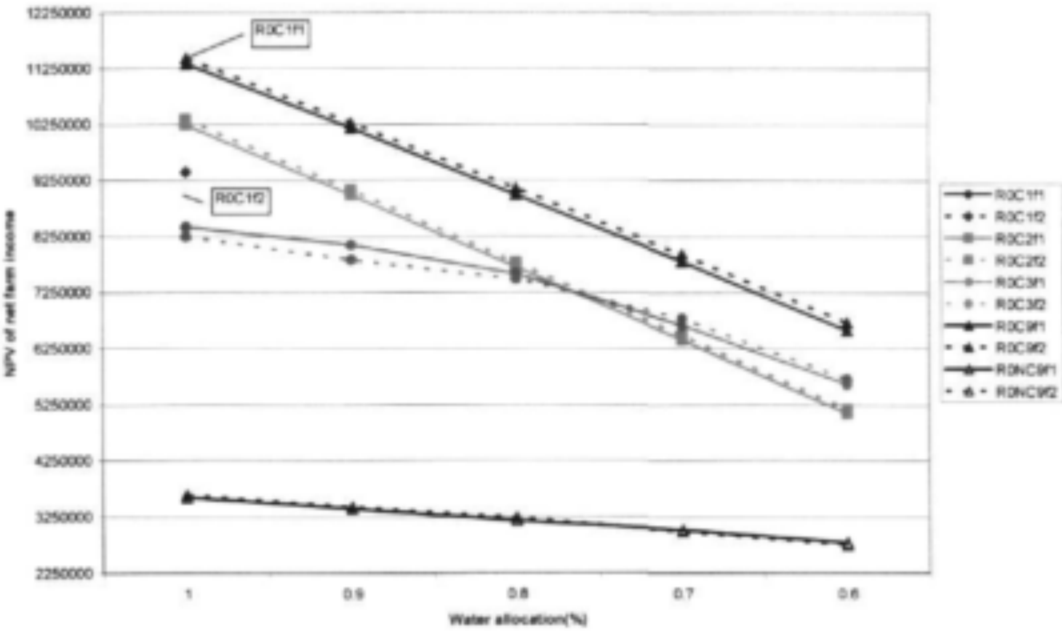


Figure 5.2: Economic tradeoffs under uniform water re-allocation situations at farm level.

The conclusion is made that long-term crops such as pecan nuts will add to the profitability of the farming business. However, an important factor that needs to be taken into account is that the transfer from a cash crop farm to a pecan nut farm will be phased in based on the availability of funds. More important is that the ability of farms with predominantly long-term crops in the crop mix will have a smaller chance to survive with water reductions. Furthermore, it will be very difficult to generalise since the current situation of a farmer plays an important role in the optimal development path.

5.3 RE-ALLOCATION OF WATER TAKING RISK INTO ACCOUNT

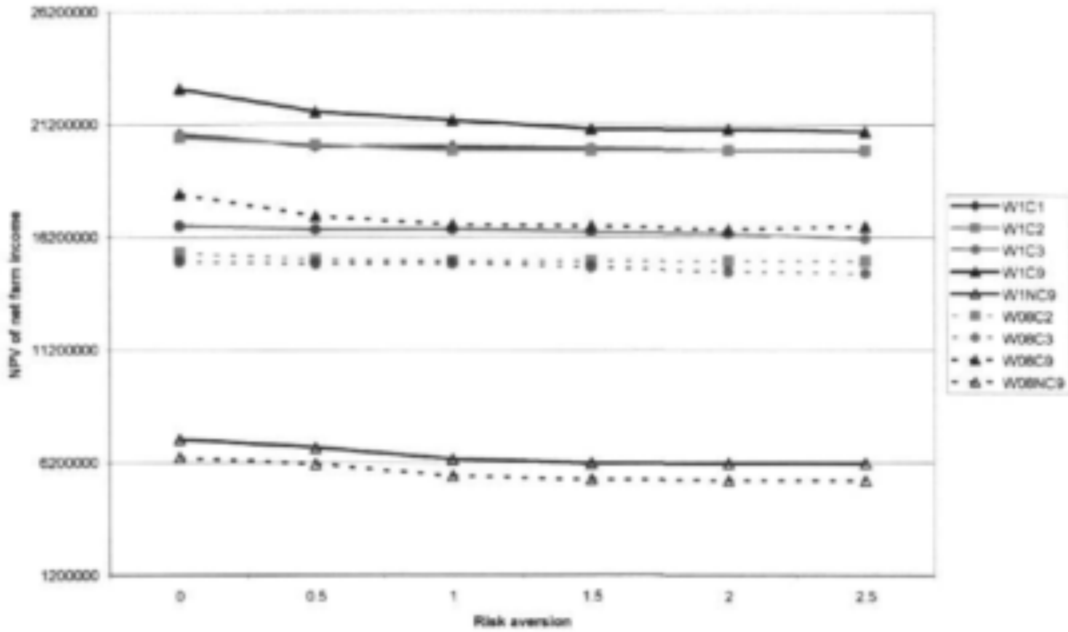


Figure 5.3: Risk tradeoffs of alternative models for two uniform water re-allocation situations at canal level.

Figure 5.3 show the risk tradeoff curves for the alternative scenarios for two water allocations at a total canal level. From Figure 5.3 it is clear that little risk tradeoff is modelled at a total canal level. Only the scenarios that do not include any long-term crops and where the optimal combination for irrigation system expansion and crop combinations are optimised without a base situation show tradeoffs.

This is a result of ignoring risk for the long-term crops which results in a zero deviation from the mean outcome. Furthermore the flood irrigation scenario (C2) does not include any deficit irrigation strategies with little variability if the crops are not deficit irrigated. The pivot scenario also does not show any tradeoff because lucerne is included in the model. The farms very quickly intensify into lucerne production due to the fact that it does not take risk into account.

The difference between the two levels of water allocation gives an idea of how effective a specific scenario is handling water deficits. Results show that Scenario C3 is more effective than Scenario C2 with Scenario NC9 being the most effective. Risk does not change the effectiveness of how water deficits are handled, which is evident from the parallel differences between the alternative water allocations.

Next the farm-level risk tradeoffs will be discussed for a full water allocation scenario as shown in Figure 5.4.

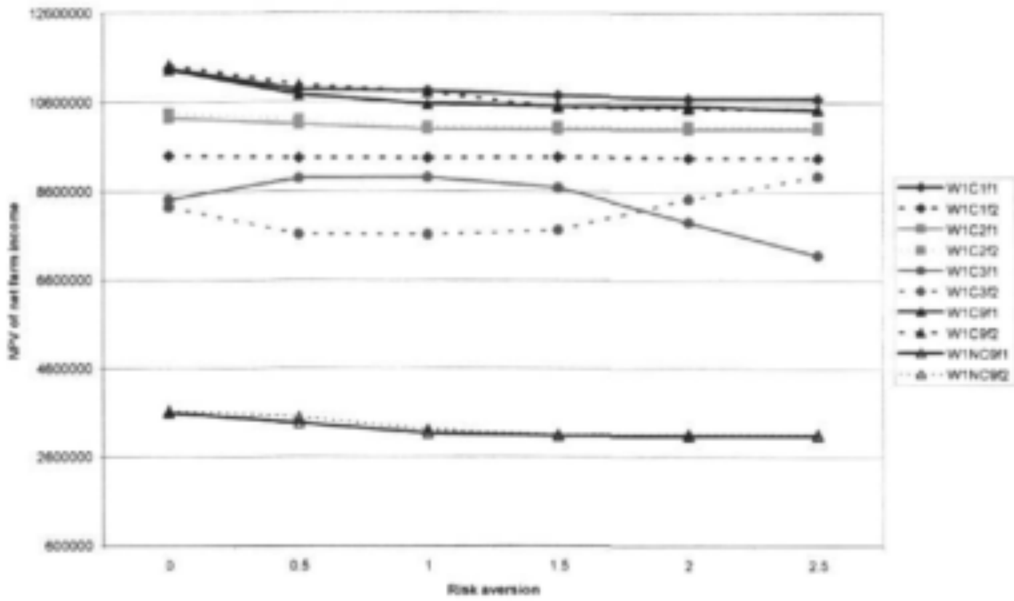


Figure 5.4: Risk tradeoffs of alternative models at farm level for a full water allocation scenario.

Scenario C1 shows that no tradeoff is modelled for farm 1, but that a tradeoff is modelled for farm 2. The reason is that farm 2 already has a significant portion of long-term crops specified as part of the current production situation and therefore due to the assumptions made has less risk associated with the outcomes. Farm 1 has to decide on the optimal development path to achieve a significant portion of long-term crops in the final crop mix and show some tradeoffs until this state is achieved.

Scenario C3 shows both positive and negative tradeoffs which is inconsistent with economic theory. However, the model is solved within a single decision-making framework. When the decisions made by one farmer influence the decisions made by another farmer, solving a single model will result in different results than when solving the separate farm models without any interaction. Thus, the combined tradeoff curves of the two farms should yield theoretically consistent results as it does when it is combined.

The conclusion is made from the results that the skeleton stochastic DLP model is able to take risk into account. However, the assumptions that no risk is modelled with long-term crops are unrealistic. Procedures should thus be developed to take production risk of long-term crops into account.

Moving towards long-term crops may increase financial risk if farmers have to borrow money to finance expansion decisions. The MOTAD procedure does not take the increased risk of financing decisions into account. Procedures still need to be developed to model risk tradeoffs with endogenously determined probability distributions that are altered by financing decisions.

5.4 TIMING OF WATER SHORTAGES

The main objective of this section is to determine what the impact of timing of water shortages is on the risk tradeoffs. Scenario S1 defines water shortages of 20% during the first three years of the analysis and S3 from years 11-13. The results are shown in Figure 5.5.

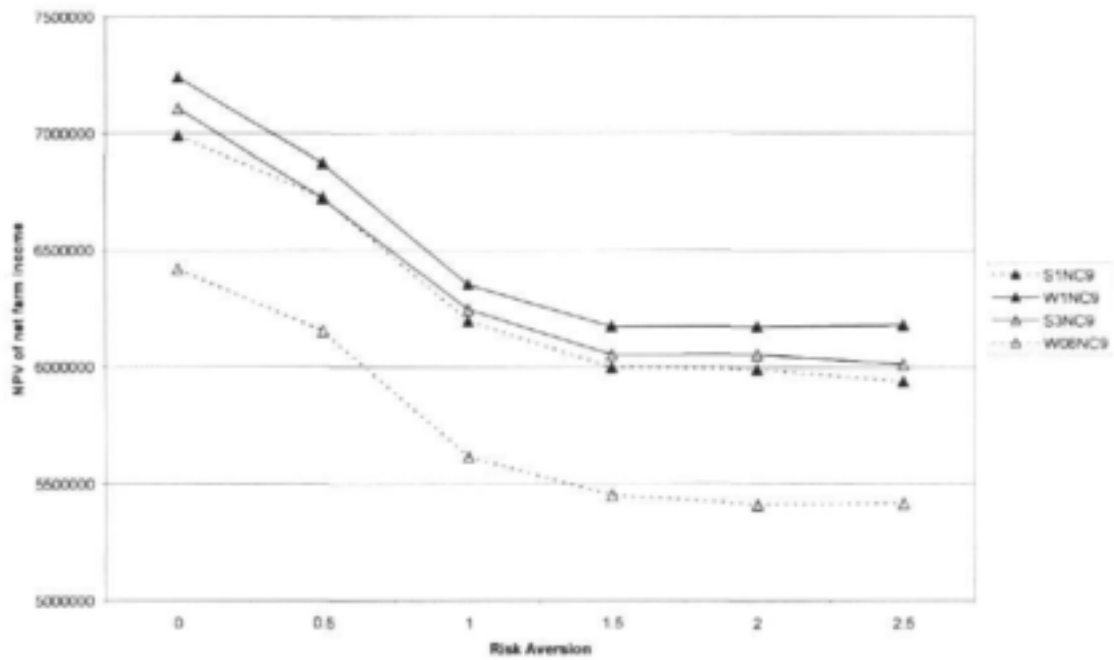


Figure 5.5: Impact of timing of water shortages on the risk tradeoffs when no long-term crops are allowed.

Significant tradeoffs are modelled to a risk aversion level of 1,5. On average the NPV is lowered by about one million Rand due to more conservative decisions. The tradeoff curves further show that water shortages during the first three years impact more severely on the NPV compared to water shortages during later years. On average there is a difference between the two scenarios of about R60 000.

The conclusion is made that the timing of water shortages will impact on the optimal development of the irrigation farm.

5.5 GENERAL CONCLUSIONS

The results presented showed that the skeleton DLP model is able to model alternative water scenarios taking risk into account. The assumption not to include risk for the long-term crops yields biased results, if risk is included in the model. However, it did highlight an important question regarding the ability of the MOTAD procedure to handle increased financial risks associated with financing options. The efficiency with which MINOS and CONOPT solve the model is very low and it takes hours to generate the results. New solvers such as CPLEX should be explored.

RESEARCH IMPLICATIONS

General

While South Africa's National Water Act and National Water Policy provide the legislative and policy framework for water allocations, they do not provide detailed strategies and approaches to promote equity, sustainability and efficiency in water use, or a process to roll this out across the country. Moreover, the process of water allocation to realise equity is likely to be both technically demanding and contentious. In future water user associations will be required to submit water management plans to ensure efficient use of water. Furthermore the water conservation and demand management strategy will put instruments in place which will promote more efficient use of water. In essence farmers will be required to produce more output per unit of input by making better use of information (irrigation scheduling), cultivating high value crops and the adoption of new, more efficient irrigation technology. The question is not whether to adopt these strategies or not, but how to proceed within a dynamic and uncertain environment.

For the first time in the history a comprehensive model is available to advise irrigation farmers on the optimal allocation of water between multiple crops under limited water supply conditions while taking the individual whole-farm situation and risk into account. The ability of the skeleton model to easily represent the situation of individual farms in terms of long-term crop composition, irrigation systems, water distribution network, location and size of irrigation fields and financial situation add to the credibility of the model results. Special care was taken during the development of the skeleton model to ensure that all relevant cash expenses and costs were accounted for in the structure of the model, thereby aiding in its ability to model real life situations more realistically. What makes the model unique is that the level of data that you have available will determine the complexity of the model and that it is very easy to conduct analyses at the whole-farm or water-user association level. The model paves the way for problem-solving applications within the field of water allocation reform and analyses of the feasibility of existing and new irrigation developments.

The procedures to incorporate risk into the programming model are very valuable. To demonstrate the applicability of the procedures developed in this research, ongoing research by Louw and Van Schalkwyk (1997) have incorporated risk into their specialised DLP models using the procedures developed in this research.

Next some specific research implications for irrigation farmers, water user associations and agricultural advisors will be discussed in more detail. Future research needs are highlighted at the end.

Irrigation Farmers

One of the most important implications for farmers is that they will be able to get advice on efficient water utilisation in the long term within a whole-farm context. The model will enable them to better plan and evaluate the feasibility of investment decisions such as the establishment of high value tree crops and irrigation technology over time (optimal development path). However, the model is also able to give decision support with respect to short-term decisions such as crop combinations, irrigation system use and allocation of water. Model results clearly indicated the sensitivity of the model to the current situation or basis in year one of the planning horizon, thereby emphasising the importance of capturing individual inputs. The structure of the model allows for differing individual inputs without altering the generalised structure of the model. Given the availability of such model, farmers should be better able to convince bank managers to access capital. The procedures in the model underpin the importance of soil water information, and irrigation farmers will only be able to prove efficient use of water if such information is used.

Water User Associations and Agricultural Advisors

The skeleton model has major implications for WUA in terms of the type of service that they can provide to irrigation farmers. WUA should start to redirect their way of thinking towards providing services and advice that will improve irrigation farming profitability and more efficient use of water. The Water Research Commission has funded several research projects to develop specialised decision support on several agricultural water management issues. The skeleton model may serve as a vehicle to integrate information from irrigation planning and scheduling models (SAPWAT and SWB), WAS (Water Distribution) and GIS to provide a complete advice service which will ensure more efficient use of water. Such a system will also provide a means to construct credible water management plans from a WUA and farmer perspective. In order to achieve this, WUA should start alliances with agricultural cooperatives and advisors with specialised knowledge. WUA that are operating such systems will definitely improve their ability to compete for scarce water and use irrigation water more efficiently.

Further research

- Decision support systems are available to farmers to reduce and manage production risk. However, little is known about the interaction between crop choice, irrigation requirement, area planted and marketing risks, because output prices are usually assumed to be constant such as in this research. This is a result of the unavailability of research capacity to quantify price risk through advanced time series analyses.
- Irrigation farming is capital intensive and many farmers are currently experiencing financial problems due to their inability to market their crops and not because they are inefficient users of water. Furthermore farmers are experiencing problems with tactical decision-making. Ways of enabling farmers to make better tactical decisions need to be explored within a workshop setting at the beginning of the planting season.

- The impact of irrigation efficiency increases on the value of irrigation water is well studied within a deterministic environment. However, within a stochastic environment (production and price risk) little is known about the impact of alternative risk management strategies on the value of water.
- The research conducted in this project focussed on how production risk impacted on irrigation farming profitability over the long run. While recognising that price risk is not taken into account, future research should focus on incorporating stochastic resource availability and assurance of water supply in the analyses.
- Further research is needed to balance the increased financial risk of adopting more efficient irrigation technology with the length of water use licences.
- An important aim of water allocation reform in South Africa is equity. When water is reallocated for equity reasons the ability of beneficiaries to use the water productively is of utmost importance (DWAF, 2004). In order to facilitate productive water use co-operatives government capacity development and support programmes (including finance) should form part of the compulsory licensing process (DWAF, 2004). Research is needed to determine optimal levels of financial support and terms of use in the presence of stochastic input and output prices.
- Within the South African environment it is imperative to demonstrate applicability of research to resource-poor farmers. Many models are typically applied to both commercial and resource-poor farmers. By implication the researchers assume that commercial and resource-poor farmers make the same decisions. However, resource-poor farmers think differently about sources of risk and strategies to manage these risks, thereby implicating a different objective function than that of commercial farmers. Research is needed to develop a decision-making model specifically aimed to support decisions made by resource-poor farmers.
- In future macro-economic analyses of both direct and indirect linkages of alternative water policies will become more important to evaluate growth possibilities and job creation. Economic growth and job creation form one of the aims of the water allocation reform process that is currently taking place in South Africa (DWAF, 2004). According to Diao, Roe and Doukkali (2005) the backward and forward linkages between the macro- and micro-programming models are of special interest when water policies are evaluated. The skeleton model may act as the micro-model in such a linked system.
- Ultimately water reallocation should be done in such a way that its impact on the environment is minimised. The skeleton model may act as a powerful tool to evaluate alternative environmental degradation control policies if linked to appropriately specified databases of environmental indicators. Armour and Viljoen (2005) have developed procedures to model the impact of water salinity on irrigation farming profitability. The skeleton model may act as a means to optimise these interactions within a DLP framework.

- The skeleton model can be used to determine the value of irrigation information within a whole-farm situation when it is linked to a suitable crop growth simulation model.

Model specific recommendations

The following model specific developments are recommended.

- The GAMS code developed to generate sequences of correlated entities for the risk programming model is a valuable product of this research. These procedures should be further developed to include other probability distributions as a means of quantifying risk.
- Procedures to handle risk associated with long-term crop production should be developed.
- Coble and Barnett (1999) stated that the extent to which stochastic and dynamic components of decision analysis are integrated within an optimisation framework is not satisfactory. Such a model should, for instance, be able to quantify the relationship between insurance and intertemporal savings, expansion and production decisions. Thus the assumption of additive risk should be relaxed by exploring maximising utility through the use of utility efficient programming methodologies.
- The procedures to optimise water allocation between competing crops taking production risk into account hinge strongly on the SAPWAT generated crop yield distributions. An implication of using relative evapotranspiration formulae to calculate yield response is that under conditions of unlimited water supply no response is calculated, resulting in a certain crop yield with no variability. However, even when water is sufficient other environmental and management factors may cause crop yields to be stochastic. Procedures should be developed for more mechanistic crop growth simulation models such as SWB (Annandale, Benadé, Jovanovic, Steyn and Sautoy, 1999) to generate the necessary information for the DLP model.
- A graphical user interface and users' guide should be developed to ease data input running of the model and interpretation of the results. Ways of linking the model to GIS databases should also be investigated.

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APPENDIX A

EXAMPLE OUTPUT FROM SKELETON MODEL

---- 624 PARAMETER dlp_gir DLP - gross irrigation requirement

	y1	y2	y3	y4
dryland1.flood.wt1.m1.cropB.y1	1211			
dryland1.flood.wt1.m1.cropB.y2	1221	1211		
dryland1.flood.wt1.m1.cropB.y3	1231	1221	1211	
dryland1.flood.wt1.m1.cropB.y4		1231	1221	1211
dryland1.flood.wt2.m1.cropB.y1	1212			
dryland1.flood.wt2.m1.cropB.y2	1222	1212		
dryland1.flood.wt2.m1.cropB.y3	1232	1222	1212	
dryland1.flood.wt2.m1.cropB.y4		1232	1222	1212
dryland1.flood.wt3.m1.cropB.y1	1213			
dryland1.flood.wt3.m1.cropB.y2	1223	1213		
dryland1.flood.wt3.m1.cropB.y3	1233	1223	1213	
dryland1.flood.wt3.m1.cropB.y4		1233	1223	1213
dryland1.pivot.wt1.m1.cropA.y1	2111			
dryland1.pivot.wt1.m1.cropA.y2		2111		
dryland1.pivot.wt1.m1.cropA.y3			2111	
dryland1.pivot.wt1.m1.cropA.y4				2111
dryland1.pivot.wt1.m1.cropB.y1	2211			
dryland1.pivot.wt1.m1.cropB.y2	2221	2211		
dryland1.pivot.wt1.m1.cropB.y3	2231	2221	2211	
dryland1.pivot.wt1.m1.cropB.y4		2231	2221	2211
dryland1.pivot.wt2.m1.cropA.y1	2112			
dryland1.pivot.wt2.m1.cropA.y2		2112		
dryland1.pivot.wt2.m1.cropA.y3			2112	
dryland1.pivot.wt2.m1.cropA.y4				2112
dryland1.pivot.wt2.m1.cropB.y1	2212			
dryland1.pivot.wt2.m1.cropB.y2	2222	2212		
dryland1.pivot.wt2.m1.cropB.y3	2232	2222	2212	
dryland1.pivot.wt2.m1.cropB.y4		2232	2222	2212
dryland1.pivot.wt3.m1.cropA.y1	2113			
dryland1.pivot.wt3.m1.cropA.y2		2113		
dryland1.pivot.wt3.m1.cropA.y3			2113	
dryland1.pivot.wt3.m1.cropA.y4				2113
dryland1.pivot.wt3.m1.cropB.y1	2213			
dryland1.pivot.wt3.m1.cropB.y2	2223	2213		
dryland1.pivot.wt3.m1.cropB.y3	2233	2223	2213	
dryland1.pivot.wt3.m1.cropB.y4		2233	2223	2213
pivot1 .pivot.wt1.m1.cropA.y1	12111			
pivot1 .pivot.wt1.m1.cropA.y2		12111		
pivot1 .pivot.wt1.m1.cropA.y3			12111	
pivot1 .pivot.wt1.m1.cropA.y4				12111
pivot1 .pivot.wt1.m1.cropB.y1	12211			
pivot1 .pivot.wt1.m1.cropB.y2	12221	12211		
pivot1 .pivot.wt1.m1.cropB.y3	12231	12221	12211	
pivot1 .pivot.wt1.m1.cropB.y4		12231	12221	12211
pivot1 .pivot.wt2.m1.cropA.y1	12112			
pivot1 .pivot.wt2.m1.cropA.y2		12112		
pivot1 .pivot.wt2.m1.cropA.y3			12112	
pivot1 .pivot.wt2.m1.cropA.y4				12112
pivot1 .pivot.wt2.m1.cropB.y1	12212			
pivot1 .pivot.wt2.m1.cropB.y2	12222	12212		
pivot1 .pivot.wt2.m1.cropB.y3	12232	12222	12212	
pivot1 .pivot.wt2.m1.cropB.y4		12232	12222	12212
pivot1 .pivot.wt3.m1.cropA.y1	12113			

pivot1	.pivot.wt3.m1.cropA.y2		12113		
pivot1	.pivot.wt3.m1.cropA.y3			12113	
pivot1	.pivot.wt3.m1.cropA.y4				12113
pivot1	.pivot.wt3.m1.cropB.y1	12213			
pivot1	.pivot.wt3.m1.cropB.y2	12223	12213		
pivot1	.pivot.wt3.m1.cropB.y3	12233	12223	12213	
pivot1	.pivot.wt3.m1.cropB.y4		12233	12223	12213
pivot2	.pivot.wt1.m1.cropA.y1	22111			
pivot2	.pivot.wt1.m1.cropA.y2		22111		
pivot2	.pivot.wt1.m1.cropA.y3			22111	
pivot2	.pivot.wt1.m1.cropA.y4				22111
pivot2	.pivot.wt1.m1.cropB.y1	22211			
pivot2	.pivot.wt1.m1.cropB.y2	22221	22211		
pivot2	.pivot.wt1.m1.cropB.y3	22231	22221	22211	
pivot2	.pivot.wt1.m1.cropB.y4		22231	22221	22211
pivot2	.pivot.wt2.m1.cropA.y1	22112			
pivot2	.pivot.wt2.m1.cropA.y2		22112		
pivot2	.pivot.wt2.m1.cropA.y3			22112	
pivot2	.pivot.wt2.m1.cropA.y4				22112
pivot2	.pivot.wt2.m1.cropB.y1	22212			
pivot2	.pivot.wt2.m1.cropB.y2	22222	22212		
pivot2	.pivot.wt2.m1.cropB.y3	22232	22222	22212	
pivot2	.pivot.wt2.m1.cropB.y4		22232	22222	22212
pivot2	.pivot.wt3.m1.cropA.y1	22113			
pivot2	.pivot.wt3.m1.cropA.y2		22113		
pivot2	.pivot.wt3.m1.cropA.y3			22113	
pivot2	.pivot.wt3.m1.cropA.y4				22113
pivot2	.pivot.wt3.m1.cropB.y1	22213			
pivot2	.pivot.wt3.m1.cropB.y2	22223	22213		
pivot2	.pivot.wt3.m1.cropB.y3	22233	22223	22213	
pivot2	.pivot.wt3.m1.cropB.y4		22233	22223	22213
pivot3	.pivot.wt1.m1.cropA.y1	32111			
pivot3	.pivot.wt1.m1.cropA.y2		32111		
pivot3	.pivot.wt1.m1.cropA.y3			32111	
pivot3	.pivot.wt1.m1.cropA.y4				32111
pivot3	.pivot.wt1.m1.cropB.y1	32211			
pivot3	.pivot.wt1.m1.cropB.y2	32221	32211		
pivot3	.pivot.wt1.m1.cropB.y3	32231	32221	32211	
pivot3	.pivot.wt1.m1.cropB.y4		32231	32221	32211
pivot3	.pivot.wt2.m1.cropA.y1	32112			
pivot3	.pivot.wt2.m1.cropA.y2		32112		
pivot3	.pivot.wt2.m1.cropA.y3			32112	
pivot3	.pivot.wt2.m1.cropA.y4				32112
pivot3	.pivot.wt2.m1.cropB.y1	32212			
pivot3	.pivot.wt2.m1.cropB.y2	32222	32212		
pivot3	.pivot.wt2.m1.cropB.y3	32232	32222	32212	
pivot3	.pivot.wt2.m1.cropB.y4		32232	32222	32212
pivot3	.pivot.wt3.m1.cropA.y1	32113			
pivot3	.pivot.wt3.m1.cropA.y2		32113		
pivot3	.pivot.wt3.m1.cropA.y3			32113	
pivot3	.pivot.wt3.m1.cropA.y4				32113
pivot3	.pivot.wt3.m1.cropB.y1	32213			
pivot3	.pivot.wt3.m1.cropB.y2	32223	32213		
pivot3	.pivot.wt3.m1.cropB.y3	32233	32223	32213	
pivot3	.pivot.wt3.m1.cropB.y4		32233	32223	32213
pivot4	.pivot.wt1.m1.cropA.y1	42111			
pivot4	.pivot.wt1.m1.cropA.y2		42111		
pivot4	.pivot.wt1.m1.cropA.y3			42111	
pivot4	.pivot.wt1.m1.cropA.y4				42111
pivot4	.pivot.wt1.m1.cropB.y1	42211			
pivot4	.pivot.wt1.m1.cropB.y2	42221	42211		
pivot4	.pivot.wt1.m1.cropB.y3	42231	42221	42211	
pivot4	.pivot.wt1.m1.cropB.y4		42231	42221	42211
pivot4	.pivot.wt2.m1.cropA.y1	42112			
pivot4	.pivot.wt2.m1.cropA.y2		42112		
pivot4	.pivot.wt2.m1.cropA.y3			42112	
pivot4	.pivot.wt2.m1.cropA.y4				42112
pivot4	.pivot.wt2.m1.cropB.y1	42212			
pivot4	.pivot.wt2.m1.cropB.y2	42222	42212		
pivot4	.pivot.wt2.m1.cropB.y3	42232	42222	42212	
pivot4	.pivot.wt2.m1.cropB.y4		42232	42222	42212
pivot4	.pivot.wt3.m1.cropA.y1	42113			

pivot4	.pivot.wt3.m1.cropA.y2		42113		
pivot4	.pivot.wt3.m1.cropA.y3			42113	
pivot4	.pivot.wt3.m1.cropA.y4				42113
pivot4	.pivot.wt3.m1.cropB.y1	42213			
pivot4	.pivot.wt3.m1.cropB.y2	42223	42213		
pivot4	.pivot.wt3.m1.cropB.y3	42233	42223	42213	
pivot4	.pivot.wt3.m1.cropB.y4		42233	42223	42213
flood1	.flood.wt1.m1.cropB.y1	51211			
flood1	.flood.wt1.m1.cropB.y2	51221	51211		
flood1	.flood.wt1.m1.cropB.y3	51231	51221	51211	
flood1	.flood.wt1.m1.cropB.y4		51231	51221	51211
flood1	.flood.wt2.m1.cropB.y1	51212			
flood1	.flood.wt2.m1.cropB.y2	51222	51212		
flood1	.flood.wt2.m1.cropB.y3	51232	51222	51212	
flood1	.flood.wt2.m1.cropB.y4		51232	51222	51212
flood1	.flood.wt3.m1.cropB.y1	51213			
flood1	.flood.wt3.m1.cropB.y2	51223	51213		
flood1	.flood.wt3.m1.cropB.y3	51233	51223	51213	
flood1	.flood.wt3.m1.cropB.y4		51233	51223	51213
flood1	.pivot.wt1.m1.cropA.y1	51111			
flood1	.pivot.wt1.m1.cropA.y2		51111		
flood1	.pivot.wt1.m1.cropA.y3			51111	
flood1	.pivot.wt1.m1.cropA.y4				51111
flood1	.pivot.wt1.m1.cropB.y1	51211			
flood1	.pivot.wt1.m1.cropB.y2	51221	51211		
flood1	.pivot.wt1.m1.cropB.y3	51231	51221	51211	
flood1	.pivot.wt1.m1.cropB.y4		51231	51221	51211
flood1	.pivot.wt2.m1.cropA.y1	51112			
flood1	.pivot.wt2.m1.cropA.y2		51112		
flood1	.pivot.wt2.m1.cropA.y3			51112	
flood1	.pivot.wt2.m1.cropA.y4				51112
flood1	.pivot.wt2.m1.cropB.y1	51212			
flood1	.pivot.wt2.m1.cropB.y2	51222	51212		
flood1	.pivot.wt2.m1.cropB.y3	51232	51222	51212	
flood1	.pivot.wt2.m1.cropB.y4		51232	51222	51212
flood1	.pivot.wt3.m1.cropA.y1	51113			
flood1	.pivot.wt3.m1.cropA.y2		51113		
flood1	.pivot.wt3.m1.cropA.y3			51113	
flood1	.pivot.wt3.m1.cropA.y4				51113
flood1	.pivot.wt3.m1.cropB.y1	51213			
flood1	.pivot.wt3.m1.cropB.y2	51223	51213		
flood1	.pivot.wt3.m1.cropB.y3	51233	51223	51213	
flood1	.pivot.wt3.m1.cropB.y4		51233	51223	51213
flood2	.flood.wt1.m1.cropB.y1	61211			
flood2	.flood.wt1.m1.cropB.y2	61221	61211		
flood2	.flood.wt1.m1.cropB.y3	61231	61221	61211	
flood2	.flood.wt1.m1.cropB.y4		61231	61221	61211
flood2	.flood.wt2.m1.cropB.y1	61212			
flood2	.flood.wt2.m1.cropB.y2	61222	61212		
flood2	.flood.wt2.m1.cropB.y3	61232	61222	61212	
flood2	.flood.wt2.m1.cropB.y4		61232	61222	61212
flood2	.flood.wt3.m1.cropB.y1	61213			
flood2	.flood.wt3.m1.cropB.y2	61223	61213		
flood2	.flood.wt3.m1.cropB.y3	61233	61223	61213	
flood2	.flood.wt3.m1.cropB.y4		61233	61223	61213
flood2	.pivot.wt1.m1.cropA.y1	61111			
flood2	.pivot.wt1.m1.cropA.y2		61111		
flood2	.pivot.wt1.m1.cropA.y3			61111	
flood2	.pivot.wt1.m1.cropA.y4				61111
flood2	.pivot.wt1.m1.cropB.y1	61211			
flood2	.pivot.wt1.m1.cropB.y2	61221	61211		
flood2	.pivot.wt1.m1.cropB.y3	61231	61221	61211	
flood2	.pivot.wt1.m1.cropB.y4		61231	61221	61211
flood2	.pivot.wt2.m1.cropA.y1	61112			
flood2	.pivot.wt2.m1.cropA.y2		61112		
flood2	.pivot.wt2.m1.cropA.y3			61112	
flood2	.pivot.wt2.m1.cropA.y4				61112
flood2	.pivot.wt2.m1.cropB.y1	61212			
flood2	.pivot.wt2.m1.cropB.y2	61222	61212		
flood2	.pivot.wt2.m1.cropB.y3	61232	61222	61212	
flood2	.pivot.wt2.m1.cropB.y4		61232	61222	61212
flood2	.pivot.wt3.m1.cropA.y1	61113			

```
flood2  .pivot.wt3.m1.cropA.y2                   61113
flood2  .pivot.wt3.m1.cropA.y3                                 61113
flood2  .pivot.wt3.m1.cropA.y4                                               61113
flood2  .pivot.wt3.m1.cropB.y1        61213
flood2  .pivot.wt3.m1.cropB.y2        61223      61213
flood2  .pivot.wt3.m1.cropB.y3        61233      61223         61213
flood2  .pivot.wt3.m1.cropB.y4                   61233         61223         61213


----    632 PARAMETER dlp_res_use  DLP - resource use

                                              y1        y2          y3          y4

labour.dryland1.flood.wt1.m1.cropB.y1       1211
labour.dryland1.flood.wt1.m1.cropB.y2       1221      1211
labour.dryland1.flood.wt1.m1.cropB.y3       1231      1221        1211
labour.dryland1.flood.wt1.m1.cropB.y4                 1231        1221        1211
labour.dryland1.flood.wt2.m1.cropB.y1       1212
labour.dryland1.flood.wt2.m1.cropB.y2       1222      1212
labour.dryland1.flood.wt2.m1.cropB.y3       1232      1222        1212
labour.dryland1.flood.wt2.m1.cropB.y4                 1232        1222        1212
labour.dryland1.flood.wt3.m1.cropB.y1       1213
labour.dryland1.flood.wt3.m1.cropB.y2       1223      1213
labour.dryland1.flood.wt3.m1.cropB.y3       1233      1223        1213
labour.dryland1.flood.wt3.m1.cropB.y4                 1233        1223        1213
labour.dryland1.pivot.wt1.m1.cropA.y1       2111
labour.dryland1.pivot.wt1.m1.cropA.y2                 2111
labour.dryland1.pivot.wt1.m1.cropA.y3                             2111
labour.dryland1.pivot.wt1.m1.cropA.y4                                         2111
labour.dryland1.pivot.wt1.m1.cropB.y1       2211
labour.dryland1.pivot.wt1.m1.cropB.y2       2221      2211
labour.dryland1.pivot.wt1.m1.cropB.y3       2231      2221        2211
labour.dryland1.pivot.wt1.m1.cropB.y4                 2231        2221        2211
labour.dryland1.pivot.wt2.m1.cropA.y1       2112
labour.dryland1.pivot.wt2.m1.cropA.y2                 2112
labour.dryland1.pivot.wt2.m1.cropA.y3                             2112
labour.dryland1.pivot.wt2.m1.cropA.y4                                         2112
labour.dryland1.pivot.wt2.m1.cropB.y1       2212
labour.dryland1.pivot.wt2.m1.cropB.y2       2222      2212
labour.dryland1.pivot.wt2.m1.cropB.y3       2232      2222        2212
labour.dryland1.pivot.wt2.m1.cropB.y4                 2232        2222        2212
labour.dryland1.pivot.wt3.m1.cropA.y1       2113
labour.dryland1.pivot.wt3.m1.cropA.y2                 2113
labour.dryland1.pivot.wt3.m1.cropA.y3                             2113
labour.dryland1.pivot.wt3.m1.cropA.y4                                         2113
labour.dryland1.pivot.wt3.m1.cropB.y1       2213
labour.dryland1.pivot.wt3.m1.cropB.y2       2223         2213
labour.dryland1.pivot.wt3.m1.cropB.y3       2233         2223     2213
labour.dryland1.pivot.wt3.m1.cropB.y4                    2233     2223        2213
labour.pivot1  .pivot.wt1.m1.cropA.y1      12111
labour.pivot1  .pivot.wt1.m1.cropA.y2                   12111
labour.pivot1  .pivot.wt1.m1.cropA.y3                            12111
labour.pivot1   .pivot.wt1.m1.cropA.y4                                       12111
labour.pivot1  .pivot.wt1.m1.cropB.y1      12211
labour.pivot1  .pivot.wt1.m1.cropB.y2      12221        12211
labour.pivot1  .pivot.wt1.m1.cropB.y3      12231        12221    12211
labour.pivot1  .pivot.wt1.m1.cropB.y4                   12231    12221       12211
labour.pivot1  .pivot.wt2.m1.cropA.y1      12112
labour.pivot1  .pivot.wt2.m1.cropA.y2                   12112
labour.pivot1  .pivot.wt2.m1.cropA.y3                            12112
labour.pivot1   .pivot.wt2.m1.cropA.y4                                       12112
labour.pivot1  .pivot.wt2.m1.cropB.y1      12212
labour.pivot1  .pivot.wt2.m1.cropB.y2      12222        12212
labour.pivot1  .pivot.wt2.m1.cropB.y3      12232        12222    12212
labour.pivot1  .pivot.wt2.m1.cropB.y4                   12232    12222       12212
labour.pivot1  .pivot.wt3.m1.cropA.y1      12113
labour.pivot1  .pivot.wt3.m1.cropA.y2                   12113
labour.pivot1  .pivot.wt3.m1.cropA.y3                            12113
labour.pivot1   .pivot.wt3.m1.cropA.y4                                       12113
labour.pivot1  .pivot.wt3.m1.cropB.y1      12213
labour.pivot1  .pivot.wt3.m1.cropB.y2      12223        12213
labour.pivot1  .pivot.wt3.m1.cropB.y3      12233        12223    12213
```

labour.pivot1	.pivot.wt3.m1.cropB.y4		12233	12223	12213
labour.pivot2	.pivot.wt1.m1.cropA.y1	22111			
labour.pivot2	.pivot.wt1.m1.cropA.y2		22111		
labour.pivot2	.pivot.wt1.m1.cropA.y3			22111	
labour.pivot2	.pivot.wt1.m1.cropA.y4				22111
labour.pivot2	.pivot.wt1.m1.cropB.y1	22211			
labour.pivot2	.pivot.wt1.m1.cropB.y2	22221	22211		
labour.pivot2	.pivot.wt1.m1.cropB.y3	22231	22221	22211	
labour.pivot2	.pivot.wt1.m1.cropB.y4		22231	22221	22211
labour.pivot2	.pivot.wt2.m1.cropA.y1	22112			
labour.pivot2	.pivot.wt2.m1.cropA.y2		22112		
labour.pivot2	.pivot.wt2.m1.cropA.y3			22112	
labour.pivot2	.pivot.wt2.m1.cropA.y4				22112
labour.pivot2	.pivot.wt2.m1.cropB.y1	22212			
labour.pivot2	.pivot.wt2.m1.cropB.y2	22222	22212		
labour.pivot2	.pivot.wt2.m1.cropB.y3	22232	22222	22212	
labour.pivot2	.pivot.wt2.m1.cropB.y4		22232	22222	22212
labour.pivot2	.pivot.wt3.m1.cropA.y1	22113			
labour.pivot2	.pivot.wt3.m1.cropA.y2		22113		
labour.pivot2	.pivot.wt3.m1.cropA.y3			22113	
labour.pivot2	.pivot.wt3.m1.cropA.y4				22113
labour.pivot2	.pivot.wt3.m1.cropB.y1	22213			
labour.pivot2	.pivot.wt3.m1.cropB.y2	22223	22213		
labour.pivot2	.pivot.wt3.m1.cropB.y3	22233	22223	22213	
labour.pivot2	.pivot.wt3.m1.cropB.y4		22233	22223	22213
labour.pivot3	.pivot.wt1.m1.cropA.y1	32111			
labour.pivot3	.pivot.wt1.m1.cropA.y2		32111		
labour.pivot3	.pivot.wt1.m1.cropA.y3			32111	
labour.pivot3	.pivot.wt1.m1.cropA.y4				32111
labour.pivot3	.pivot.wt1.m1.cropB.y1	32211			
labour.pivot3	.pivot.wt1.m1.cropB.y2	32221	32211		
labour.pivot3	.pivot.wt1.m1.cropB.y3	32231	32221	32211	
labour.pivot3	.pivot.wt1.m1.cropB.y4		32231	32221	32211
labour.pivot3	.pivot.wt2.m1.cropA.y1	32112			
labour.pivot3	.pivot.wt2.m1.cropA.y2		32112		
labour.pivot3	.pivot.wt2.m1.cropA.y3			32112	
labour.pivot3	.pivot.wt2.m1.cropA.y4				32112
labour.pivot3	.pivot.wt2.m1.cropB.y1	32212			
labour.pivot3	.pivot.wt2.m1.cropB.y2	32222	32212		
labour.pivot3	.pivot.wt2.m1.cropB.y3	32232	32222	32212	
labour.pivot3	.pivot.wt2.m1.cropB.y4		32232	32222	32212
labour.pivot3	.pivot.wt3.m1.cropA.y1	32113			
labour.pivot3	.pivot.wt3.m1.cropA.y2		32113		
labour.pivot3	.pivot.wt3.m1.cropA.y3			32113	
labour.pivot3	.pivot.wt3.m1.cropA.y4				32113
labour.pivot3	.pivot.wt3.m1.cropB.y1	32213			
labour.pivot3	.pivot.wt3.m1.cropB.y2	32223	32213		
labour.pivot3	.pivot.wt3.m1.cropB.y3	32233	32223	32213	
labour.pivot3	.pivot.wt3.m1.cropB.y4		32233	32223	32213
labour.pivot4	.pivot.wt1.m1.cropA.y1	42111			
labour.pivot4	.pivot.wt1.m1.cropA.y2		42111		
labour.pivot4	.pivot.wt1.m1.cropA.y3			42111	
labour.pivot4	.pivot.wt1.m1.cropA.y4				42111
labour.pivot4	.pivot.wt1.m1.cropB.y1	42211			
labour.pivot4	.pivot.wt1.m1.cropB.y2	42221	42211		
labour.pivot4	.pivot.wt1.m1.cropB.y3	42231	42221	42211	
labour.pivot4	.pivot.wt1.m1.cropB.y4		42231	42221	42211
labour.pivot4	.pivot.wt2.m1.cropA.y1	42112			
labour.pivot4	.pivot.wt2.m1.cropA.y2		42112		
labour.pivot4	.pivot.wt2.m1.cropA.y3			42112	
labour.pivot4	.pivot.wt2.m1.cropA.y4				42112
labour.pivot4	.pivot.wt2.m1.cropB.y1	42212			
labour.pivot4	.pivot.wt2.m1.cropB.y2	42222	42212		
labour.pivot4	.pivot.wt2.m1.cropB.y3	42232	42222	42212	
labour.pivot4	.pivot.wt2.m1.cropB.y4		42232	42222	42212
labour.pivot4	.pivot.wt3.m1.cropA.y1	42113			
labour.pivot4	.pivot.wt3.m1.cropA.y2		42113		
labour.pivot4	.pivot.wt3.m1.cropA.y3			42113	
labour.pivot4	.pivot.wt3.m1.cropA.y4				42113
labour.pivot4	.pivot.wt3.m1.cropB.y1	42213			
labour.pivot4	.pivot.wt3.m1.cropB.y2	42223	42213		
labour.pivot4	.pivot.wt3.m1.cropB.y3	42233	42223	42213	

labour.pivot4	.pivot.wt3.m1.cropB.y4		42233	42223	42213
labour.flood1	.flood.wt1.m1.cropB.y1	51211			
labour.flood1	.flood.wt1.m1.cropB.y2	51221	51211		
labour.flood1	.flood.wt1.m1.cropB.y3	51231	51221	51211	
labour.flood1	.flood.wt1.m1.cropB.y4		51231	51221	51211
labour.flood1	.flood.wt2.m1.cropB.y1	51212			
labour.flood1	.flood.wt2.m1.cropB.y2	51222	51212		
labour.flood1	.flood.wt2.m1.cropB.y3	51232	51222	51212	
labour.flood1	.flood.wt2.m1.cropB.y4		51232	51222	51212
labour.flood1	.flood.wt3.m1.cropB.y1	51213			
labour.flood1	.flood.wt3.m1.cropB.y2	51223	51213		
labour.flood1	.flood.wt3.m1.cropB.y3	51233	51223	51213	
labour.flood1	.flood.wt3.m1.cropB.y4		51233	51223	51213
labour.flood1	.pivot.wt1.m1.cropA.y1	51111			
labour.flood1	.pivot.wt1.m1.cropA.y2		51111		
labour.flood1	.pivot.wt1.m1.cropA.y3			51111	
labour.flood1	.pivot.wt1.m1.cropA.y4				51111
labour.flood1	.pivot.wt1.m1.cropB.y1	51211			
labour.flood1	.pivot.wt1.m1.cropB.y2	51221	51211		
labour.flood1	.pivot.wt1.m1.cropB.y3	51231	51221	51211	
labour.flood1	.pivot.wt1.m1.cropB.y4		51231	51221	51211
labour.flood1	.pivot.wt2.m1.cropA.y1	51112			
labour.flood1	.pivot.wt2.m1.cropA.y2		51112		
labour.flood1	.pivot.wt2.m1.cropA.y3			51112	
labour.flood1	.pivot.wt2.m1.cropA.y4				51112
labour.flood1	.pivot.wt2.m1.cropB.y1	51212			
labour.flood1	.pivot.wt2.m1.cropB.y2	51222	51212		
labour.flood1	.pivot.wt2.m1.cropB.y3	51232	51222	51212	
labour.flood1	.pivot.wt2.m1.cropB.y4		51232	51222	51212
labour.flood1	.pivot.wt3.m1.cropA.y1	51113			
labour.flood1	.pivot.wt3.m1.cropA.y2		51113		
labour.flood1	.pivot.wt3.m1.cropA.y3			51113	
labour.flood1	.pivot.wt3.m1.cropA.y4				51113
labour.flood1	.pivot.wt3.m1.cropB.y1	51213			
labour.flood1	.pivot.wt3.m1.cropB.y2	51223	51213		
labour.flood1	.pivot.wt3.m1.cropB.y3	51233	51223	51213	
labour.flood1	.pivot.wt3.m1.cropB.y4		51233	51223	51213
labour.flood2	.flood.wt1.m1.cropB.y1	61211			
labour.flood2	.flood.wt1.m1.cropB.y2	61221	61211		
labour.flood2	.flood.wt1.m1.cropB.y3	61231	61221	61211	
labour.flood2	.flood.wt1.m1.cropB.y4		61231	61221	61211
labour.flood2	.flood.wt2.m1.cropB.y1	61212			
labour.flood2	.flood.wt2.m1.cropB.y2	61222	61212		
labour.flood2	.flood.wt2.m1.cropB.y3	61232	61222	61212	
labour.flood2	.flood.wt2.m1.cropB.y4		61232	61222	61212
labour.flood2	.flood.wt3.m1.cropB.y1	61213			
labour.flood2	.flood.wt3.m1.cropB.y2	61223	61213		
labour.flood2	.flood.wt3.m1.cropB.y3	61233	61223	61213	
labour.flood2	.flood.wt3.m1.cropB.y4		61233	61223	61213
labour.flood2	.pivot.wt1.m1.cropA.y1	61111			
labour.flood2	.pivot.wt1.m1.cropA.y2		61111		
labour.flood2	.pivot.wt1.m1.cropA.y3			61111	
labour.flood2	.pivot.wt1.m1.cropA.y4				61111
labour.flood2	.pivot.wt1.m1.cropB.y1	61211			
labour.flood2	.pivot.wt1.m1.cropB.y2	61221	61211		
labour.flood2	.pivot.wt1.m1.cropB.y3	61231	61221	61211	
labour.flood2	.pivot.wt1.m1.cropB.y4		61231	61221	61211
labour.flood2	.pivot.wt2.m1.cropA.y1	61112			
labour.flood2	.pivot.wt2.m1.cropA.y2		61112		
labour.flood2	.pivot.wt2.m1.cropA.y3			61112	
labour.flood2	.pivot.wt2.m1.cropA.y4				61112
labour.flood2	.pivot.wt2.m1.cropB.y1	61212			
labour.flood2	.pivot.wt2.m1.cropB.y2	61222	61212		
labour.flood2	.pivot.wt2.m1.cropB.y3	61232	61222	61212	
labour.flood2	.pivot.wt2.m1.cropB.y4		61232	61222	61212
labour.flood2	.pivot.wt3.m1.cropA.y1	61113			
labour.flood2	.pivot.wt3.m1.cropA.y2		61113		
labour.flood2	.pivot.wt3.m1.cropA.y3			61113	
labour.flood2	.pivot.wt3.m1.cropA.y4				61113
labour.flood2	.pivot.wt3.m1.cropB.y1	61213			
labour.flood2	.pivot.wt3.m1.cropB.y2	61223	61213		
labour.flood2	.pivot.wt3.m1.cropB.y3	61233	61223	61213	

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labour.flood2  .pivot.wt3.ml.cropB.y4                   61233      61223        61213

----     640 PARAMETER dlp_crop_occu  DLP - irrigation system occupation

                  y1          y2          y3          y4

cropA.wt1.y1       1
cropA.wt1.y2                   1
cropA.wt1.y3                               1
cropA.wt1.y4                                           1
cropB.wt1.y1       1
cropB.wt1.y2       1           1
cropB.wt1.y3       1           1           1
cropB.wt1.y4                   1           1           1
cropB.wt2.y1       1
cropB.wt2.y2       1           1
cropB.wt2.y3       1           1           1
cropB.wt2.y4                   1           1           1
cropB.wt3.y1       1
cropB.wt3.y2       1           1
cropB.wt3.y3       1           1           1
cropB.wt3.y4                   1           1           1


----     648 PARAMETER dlp_irri_occu  DLP - irrigation system occupation

                  y1          y2          y3          y4

flood.y1           1
flood.y2                       1
flood.y3                                   1
flood.y4                                               1
pivot.y1           1
pivot.y2           1           1
pivot.y3           1           1           1
pivot.y4                       1           1           1


----     656 PARAMETER dlp_invest  DLP - investment capital

                              y1          y2          y3          y4

dryland1.flood.y1           1000
dryland1.flood.y2                       1000
dryland1.flood.y3                                   1000
dryland1.flood.y4                                               1000
dryland1.pivot.y1           2000
dryland1.pivot.y2                       2000
dryland1.pivot.y3                                   2000
dryland1.pivot.y4                                               2000
pivot1   .pivot.y1         12000
pivot1   .pivot.y2                     12000
pivot1   .pivot.y3                                 12000
pivot1   .pivot.y4                                             12000
pivot2   .pivot.y1         22000
pivot2   .pivot.y2                     22000
pivot2   .pivot.y3                                 22000
pivot2   .pivot.y4                                             22000
pivot3   .pivot.y1         32000
pivot3   .pivot.y2                     32000
pivot3   .pivot.y3                                 32000
pivot3   .pivot.y4                                             32000
pivot4   .pivot.y1         42000
pivot4   .pivot.y2                     42000
pivot4   .pivot.y3                                 42000
pivot4   .pivot.y4                                             42000
flood1   .flood.y1         51000
flood1   .flood.y2                     51000
flood1   .flood.y3                                 51000
flood1   .flood.y4                                             51000
flood1   .pivot.y1         52000
flood1   .pivot.y2                     52000
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flood1  .pivot.y3                                52000
flood1  .pivot.y4                                              52000
flood2  .flood.y1         61000
flood2  .flood.y2                      61000
flood2  .flood.y3                                61000
flood2  .flood.y4                                              61000
flood2  .pivot.y1         62000
flood2  .pivot.y2                      62000
flood2  .pivot.y3                                62000
flood2  .pivot.y4                                              62000


----    664 PARAMETER dlp_salvage  DLP - salvage values

                             y1          y2          y3          y4

dryland1.flood.y1          1000
dryland1.flood.y2                      1000
dryland1.flood.y3                                  1000
dryland1.flood.y4                                              1000
dryland1.pivot.y3           400
dryland1.pivot.y4                       400
pivot1  .pivot.y3          2400
pivot1  .pivot.y4                      2400
pivot2  .pivot.y3          4400
pivot2  .pivot.y4                      4400
pivot3  .pivot.y3          6400
pivot3  .pivot.y4                      6400
pivot4  .pivot.y3          8400
pivot4  .pivot.y4                      8400
flood1  .flood.y1         51000
flood1  .flood.y2                     51000
flood1  .flood.y3                                 51000
flood1  .flood.y4                                             51000
flood1  .pivot.y3         10400
flood1  .pivot.y4                     10400
flood2  .flood.y1         61000
flood2  .flood.y2                     61000
flood2  .flood.y3                                 61000
flood2  .flood.y4                                             61000
flood2  .pivot.y3         12400
flood2  .pivot.y4                     12400


----    676 PARAMETER dlp_prodincome  DLP - production income

INDEX 1          = farm1

                                          y1          y2          y3          y4

dryland1.dry  .m1.cropA.y1              3000
dryland1.dry  .m1.cropA.y2                          3000
dryland1.dry  .m1.cropA.y3                                      3000
dryland1.dry  .m1.cropA.y4                                                  3000
dryland1.flood.m1.cropB.y1             10000
dryland1.flood.m1.cropB.y2             12000       10000
dryland1.flood.m1.cropB.y3             14000       12000       10000
dryland1.flood.m1.cropB.y4                         14000       12000       10000
dryland1.pivot.m1.cropA.y1              9000
dryland1.pivot.m1.cropA.y2                          9000
dryland1.pivot.m1.cropA.y3                                      9000
dryland1.pivot.m1.cropA.y4                                                  9000
dryland1.pivot.m1.cropB.y1             14000
dryland1.pivot.m1.cropB.y2             16000       14000
dryland1.pivot.m1.cropB.y3             16000       16000       14000
dryland1.pivot.m1.cropB.y4                         16000       16000       14000
pivot1  .pivot.m1.cropA.y1              9000
pivot1  .pivot.m1.cropA.y2                          9000
pivot1  .pivot.m1.cropA.y3                                      9000
pivot1  .pivot.m1.cropA.y4                                                  9000
pivot1  .pivot.m1.cropB.y1             14000
pivot1  .pivot.m1.cropB.y2             16000       14000
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pivot1  .pivot.m1.cropB.y3          18000      16000      14000
pivot1  .pivot.m1.cropB.y4                     18000      16000      14000
pivot2  .pivot.m1.cropA.y1           9000
pivot2  .pivot.m1.cropA.y2                      9000
pivot2  .pivot.m1.cropA.y3                                 9000
pivot2  .pivot.m1.cropA.y4                                            9000
pivot2  .pivot.m1.cropB.y1          14000
pivot2  .pivot.m1.cropB.y2          16000      14000
pivot2  .pivot.m1.cropB.y3          18000      16000      14000
pivot2  .pivot.m1.cropB.y4                     18000      16000      14000
pivot3  .pivot.m1.cropA.y1           9000
pivot3  .pivot.m1.cropA.y2                      9000
pivot3  .pivot.m1.cropA.y3                                 9000
pivot3  .pivot.m1.cropA.y4                                            9000
pivot3  .pivot.m1.cropB.y1          14000
pivot3  .pivot.m1.cropB.y2          16000      14000
pivot3  .pivot.m1.cropB.y3          18000      16000      14000
pivot3  .pivot.m1.cropB.y4                     18000      16000      14000

        676 PARAMETER dlp_prodincome  DLP - production income

INDEX 1          = farm2

                                       y1         y2         y3         y4

pivot4.pivot.m1.cropA.y1             9000
pivot4.pivot.m1.cropA.y2                        9000
pivot4.pivot.m1.cropA.y3                                   9000
pivot4.pivot.m1.cropA.y4                                              9000
pivot4.pivot.m1.cropB.y1            14000
pivot4.pivot.m1.cropB.y2            16000      14000
pivot4.pivot.m1.cropB.y3            18000      16000      14000
pivot4.pivot.m1.cropB.y4                       18000      16000      14000
flood1.flood.m1.cropB.y1            10000
flood1.flood.m1.cropB.y2            12000      10000
flood1.flood.m1.cropB.y3            14000      12000      10000
flood1.flood.m1.cropB.y4                       14000      12000      10000
flood2.flood.m1.cropB.y1            10000
flood2.flood.m1.cropB.y2            12000      10000
flood2.flood.m1.cropB.y3            14000      12000      10000
flood2.flood.m1.cropB.y4                       14000      12000      10000


----    684 PARAMETER dlp_operating  DLP - operating capital

INDEX 1          = dryland1

                          y1         y2         y3         y4

flood.m1.cropB.y1        221
flood.m1.cropB.y2        222        221
flood.m1.cropB.y3        223        222        221
flood.m1.cropB.y4                   223        222        221
pivot.m1.cropA.y1        211
pivot.m1.cropA.y2                   211
pivot.m1.cropA.y3                              211
pivot.m1.cropA.y4                                         211
pivot.m1.cropB.y1        221
pivot.m1.cropB.y2        222        221
pivot.m1.cropB.y3        223        222        221
pivot.m1.cropB.y4                   223        222        221

INDEX 1          = pivot1

                          y1         y2         y3         y4

pivot.m1.cropA.y1       1211
pivot.m1.cropA.y2                  1211
pivot.m1.cropA.y3                             1211
pivot.m1.cropA.y4                                        1211
pivot.m1.cropB.y1       1221
pivot.m1.cropB.y2       1222       1221
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pivot.m1.cropB.y3          1223        1222        1221
pivot.m1.cropB.y4                      1223        1222        1221

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        684 PARAMETER dlp_operating  DLP - operating capital

INDEX 1          = pivot2

                             y1          y2          y3          y4

pivot.m1.cropA.y1          2211
pivot.m1.cropA.y2                      2211
pivot.m1.cropA.y3                                  2211
pivot.m1.cropA.y4                                              2211
pivot.m1.cropB.y1          2221
pivot.m1.cropB.y2          2222        2221
pivot.m1.cropB.y3          2223        2222        2221
pivot.m1.cropB.y4                      2223        2222        2221

INDEX 1          = pivot3

                             y1          y2          y3          y4

pivot.m1.cropA.y1          3211
pivot.m1.cropA.y2                      3211
pivot.m1.cropA.y3                                  3211
pivot.m1.cropA.y4                                              3211
pivot.m1.cropB.y1          3221
pivot.m1.cropB.y2          3222        3221
pivot.m1.cropB.y3          3223        3222        3221
pivot.m1.cropB.y4                      3223        3222        3221

INDEX 1          = pivot4

                             y1          y2          y3          y4

pivot.m1.cropA.y1          4211
pivot.m1.cropA.y2                      4211
pivot.m1.cropA.y3                                  4211
pivot.m1.cropA.y4                                              4211
pivot.m1.cropB.y1          4221
pivot.m1.cropB.y2          4222        4221
pivot.m1.cropB.y3          4223        4222        4221
pivot.m1.cropB.y4                      4223        4222        4221

INDEX 1          = flood1

                             y1          y2          y3          y4

flood.m1.cropB.y1          5221
flood.m1.cropB.y2          5222        5221
flood.m1.cropB.y3          5223        5222        5221
flood.m1.cropB.y4                      5223        5222        5221
pivot.m1.cropA.y1          5211
pivot.m1.cropA.y2                      5211
pivot.m1.cropA.y3                                  5211
pivot.m1.cropA.y4                                              5211
pivot.m1.cropB.y1          5221
pivot.m1.cropB.y2          5222        5221
pivot.m1.cropB.y3          5223        5222        5221
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        684 PARAMETER dlp_operating  DLP - operating capital

INDEX 1          = flood1

                             y1          y2          y3          y4

pivot.ml.cropB.y4                      5223        5222        5221

INDEX 1          = flood2

                             y1          y2          y3          y4

flood.ml.cropB.y1          6221
flood.ml.cropB.y2          6222        6221
flood.ml.cropB.y3          6223        6222        6221
flood.ml.cropB.y4                      6223        6222        6221
pivot.ml.cropA.y1          6211
pivot.ml.cropA.y2                      6211
pivot.ml.cropA.y3                                  6211
pivot.ml.cropA.y4                                              6211
pivot.ml.cropB.y1          6221
pivot.ml.cropB.y2          6222        6221
pivot.ml.cropB.y3          6223        6222        6221
pivot.ml.cropB.y4                      6223        6222        6221


----    691 PARAMETER dlp_sys_networth  DLP - irrigation system net worth

                             y1          y2          y3          y4

dryland1.flood.y1          1000
dryland1.flood.y2                      1000
dryland1.flood.y3                                  1000
dryland1.flood.y4                                              1000
dryland1.pivot.y1          1467
dryland1.pivot.y2           933        1467
dryland1.pivot.y3           400         933        1467
dryland1.pivot.y4                       400         933        1467
pivot1  .pivot.y1          8800
pivot1  .pivot.y2          5600        8800
pivot1  .pivot.y3          2400        5600        8800
pivot1  .pivot.y4                      2400        5600        8800
pivot2  .pivot.y1         16133
pivot2  .pivot.y2         10267       16133
pivot2  .pivot.y3          4400       10267       16133
pivot2  .pivot.y4                      4400       10267       16133
pivot3  .pivot.y1         23467
pivot3  .pivot.y2         14933       23467
pivot3  .pivot.y3          6400       14933       23467
pivot3  .pivot.y4                      6400       14933       23467
pivot4  .pivot.y1         30800
pivot4  .pivot.y2         19600       30800
pivot4  .pivot.y3          8400       19600       30800
pivot4  .pivot.y4                      8400       19600       30800
flood1  .flood.y1         51000
flood1  .flood.y2                     51000
flood1  .flood.y3                                 51000
flood1  .flood.y4                                             51000
flood1  .pivot.y1         38133
flood1  .pivot.y2         24267       38133
flood1  .pivot.y3         10400       24267       38133
flood1  .pivot.y4                     10400       24267       38133
flood2  .flood.y1         61000
flood2  .flood.y2                     61000
flood2  .flood.y3                                 61000
flood2  .flood.y4                                             61000
flood2  .pivot.y1         45467
```

	y1	y2	y3	y4
flood2 .pivot.y2	28933	45467		
flood2 .pivot.y3	12400	28933	45467	
flood2 .pivot.y4		12400	28933	45467

---- 699 PARAMETER dlp_taxdep DLP - depreciation tax deduction

	y1	y2	y3	y4
dryland1.flood.y1	500			
dryland1.flood.y2	300	500		
dryland1.flood.y3	200	300	500	
dryland1.flood.y4		200	300	500
dryland1.pivot.y1	1000			
dryland1.pivot.y2	600	1000		
dryland1.pivot.y3	400	600	1000	
dryland1.pivot.y4		400	600	1000
pivot1 .pivot.y1	6000			
pivot1 .pivot.y2	3600	6000		
pivot1 .pivot.y3	2400	3600	6000	
pivot1 .pivot.y4		2400	3600	6000
pivot2 .pivot.y1	11000			
pivot2 .pivot.y2	6600	11000		
pivot2 .pivot.y3	4400	6600	11000	
pivot2 .pivot.y4		4400	6600	11000
pivot3 .pivot.y1	16000			
pivot3 .pivot.y2	9600	16000		
pivot3 .pivot.y3	6400	9600	16000	
pivot3 .pivot.y4		6400	9600	16000
pivot4 .pivot.y1	21000			
pivot4 .pivot.y2	12600	21000		
pivot4 .pivot.y3	8400	12600	21000	
pivot4 .pivot.y4		8400	12600	21000
flood1 .flood.y1	25500			
flood1 .flood.y2	15300	25500		
flood1 .flood.y3	10200	15300	25500	
flood1 .flood.y4		10200	15300	25500
flood1 .pivot.y1	26000			
flood1 .pivot.y2	15600	26000		
flood1 .pivot.y3	10400	15600	26000	
flood1 .pivot.y4		10400	15600	26000
flood2 .flood.y1	30500			
flood2 .flood.y2	18300	30500		
flood2 .flood.y3	12200	18300	30500	
flood2 .flood.y4		12200	18300	30500
flood2 .pivot.y1	31000			
flood2 .pivot.y2	18600	31000		
flood2 .pivot.y3	12400	18600	31000	
flood2 .pivot.y4		12400	18600	31000

---- 713 PARAMETER dlp_payment

	y1	y2	y3	y4
farm1.outstanding.y1	0.7174			
farm1.outstanding.y2	0.3868	0.7174		
farm1.outstanding.y3	-3.3307E-16	0.3868	0.7174	
farm1.outstanding.y4		-3.3307E-16	0.3868	0.7174
farm1.interest .y1	0.1700			
farm1.interest .y2	0.1220	0.1700		
farm1.interest .y3	0.0658	0.1220	0.1700	
farm1.interest .y4		0.0658	0.1220	0.1700
farm1.principal .y1	0.2826			
farm1.principal .y2	0.3306	0.2826		
farm1.principal .y3	0.3868	0.3306	0.2826	
farm1.principal .y4		0.3868	0.3306	0.2826
farm2.outstanding.y1	0.7174			
farm2.outstanding.y2	0.3868	0.7174		
farm2.outstanding.y3	-3.3307E-16	0.3868	0.7174	
farm2.outstanding.y4		-3.3307E-16	0.3868	0.7174
farm2.interest .y1	0.1700			
farm2.interest .y2	0.1220	0.1700		

```
farm2.interest   .y3          0.0658      0.1220      0.1700
farm2.interest   .y4                      0.0658      0.1220      0.1700
farm2.principal  .y1          0.2826
farm2.principal  .y2          0.3306      0.2826
farm2.principal  .y3          0.3868      0.3306      0.2826
farm2.principal  .y4                      0.3868      0.3306      0.2826

----    724 PARAMETER dlp_cur_gir  DLP - current gross irrigation requirement

INDEX 1          = pivot1

                           y1

pivot.wt1.m1.cropB.y1    12221
pivot.wt1.m1.cropB.y2    12231
pivot.wt2.m1.cropB.y1    12222
pivot.wt2.m1.cropB.y2    12232
pivot.wt3.m1.cropB.y1    12223
pivot.wt3.m1.cropB.y2    12233

INDEX 1          = pivot2

                           y1

pivot.wt1.m1.cropB.y1    22231
pivot.wt2.m1.cropB.y1    22232
pivot.wt3.m1.cropB.y1    22233

INDEX 1          = pivot4

                           y1

pivot.wt1.m1.cropB.y1    42221
pivot.wt1.m1.cropB.y2    42231
pivot.wt2.m1.cropB.y1    42222
pivot.wt2.m1.cropB.y2    42232
pivot.wt3.m1.cropB.y1    42223
pivot.wt3.m1.cropB.y2    42233


----    732 PARAMETER dlp_cur_res_use  DLP - current resource use

INDEX 1          = labour

                                       y1

pivot1.pivot.wt1.m1.cropB.y1         12221
pivot1.pivot.wt1.m1.cropB.y2         12231
pivot1.pivot.wt2.m1.cropB.y1         12222
pivot1.pivot.wt2.m1.cropB.y2         12232
pivot1.pivot.wt3.m1.cropB.y1         12223
pivot1.pivot.wt3.m1.cropB.y2         12233
pivot2.pivot.wt1.m1.cropB.y1         22231
pivot2.pivot.wt2.m1.cropB.y1         22232
pivot2.pivot.wt3.m1.cropB.y1         22233
pivot4.pivot.wt1.m1.cropB.y1         42221
pivot4.pivot.wt1.m1.cropB.y2         42231
pivot4.pivot.wt2.m1.cropB.y1         42222
pivot4.pivot.wt2.m1.cropB.y2         42232
pivot4.pivot.wt3.m1.cropB.y1         42223
pivot4.pivot.wt3.m1.cropB.y2         42233
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----    745 PARAMETER cur_crop_occu_flag

                          y1          y2          y3          y4

pivot1.cropB.y1            1
pivot1.cropB.y2            1           1
pivot1.cropB.y3                        1           1
pivot1.cropB.y4                                    1           1
pivot2.cropB.y1            1
pivot2.cropB.y2                        1
pivot2.cropB.y3                                    1
pivot2.cropB.y4                                                1
pivot4.cropB.y1            1
pivot4.cropB.y2            1           1
pivot4.cropB.y3                        1           1
pivot4.cropB.y4                                    1           1

----     748  PARAMETER  dlp_cur_crop_occu  DLP - current  land  occupation  by
crops

                          y1          y2          y3          y4

pivot1.wt1.cropB.y1        1
pivot1.wt1.cropB.y2        1           1
pivot1.wt1.cropB.y3                    1           1
pivot1.wt1.cropB.y4                                1           1
pivot1.wt2.cropB.y1        1
pivot1.wt2.cropB.y2        1           1
pivot1.wt2.cropB.y3                    1           1
pivot1.wt2.cropB.y4                                1           1
pivot1.wt3.cropB.y1        1
pivot1.wt3.cropB.y2        1           1
pivot1.wt3.cropB.y3                    1           1
pivot1.wt3.cropB.y4                                1           1
pivot2.wt1.cropB.y1        1
pivot2.wt1.cropB.y2                    1
pivot2.wt1.cropB.y3                                1
pivot2.wt1.cropB.y4                                            1
pivot2.wt2.cropB.y1        1
pivot2.wt2.cropB.y2                    1
pivot2.wt2.cropB.y3                                1
pivot2.wt2.cropB.y4                                            1
pivot2.wt3.cropB.y1        1
pivot2.wt3.cropB.y2                    1
pivot2.wt3.cropB.y3                                1
pivot2.wt3.cropB.y4                                            1
pivot4.wt1.cropB.y1        1
pivot4.wt1.cropB.y2        1           1
pivot4.wt1.cropB.y3                    1           1
pivot4.wt1.cropB.y4                                1           1
pivot4.wt2.cropB.y1        1
pivot4.wt2.cropB.y2        1           1
pivot4.wt2.cropB.y3                    1           1
pivot4.wt2.cropB.y4                                1           1
pivot4.wt3.cropB.y1        1
pivot4.wt3.cropB.y2        1           1
pivot4.wt3.cropB.y3                    1           1
pivot4.wt3.cropB.y4                                1           1

----     757  PARAMETER  dlp_cur_irri_occu   DLP - current  irrigation  system
occupation

                          y1

pivot1.pivot.y1            1
pivot1.pivot.y2            1
```

```
pivot2.pivot.y1             1
pivot4.pivot.y1             1
pivot4.pivot.y2             1


----     769 PARAMETER dlp_salvage  DLP - salvage values

                           y1          y2          y3          y4

dryland1.flood.y1        1000
dryland1.flood.y2                    1000
dryland1.flood.y3                                1000
dryland1.flood.y4                                            1000
dryland1.pivot.y3         400
dryland1.pivot.y4                     400
pivot1  .pivot.y3        2400
pivot1  .pivot.y4                    2400
pivot2  .pivot.y3        4400
pivot2  .pivot.y4                    4400
pivot3  .pivot.y3        6400
pivot3  .pivot.y4                    6400
pivot4  .pivot.y3        8400
pivot4  .pivot.y4                    8400
flood1  .flood.y1       51000
flood1  .flood.y2                   51000
flood1  .flood.y3                               51000
flood1  .flood.y4                                           51000
flood1  .pivot.y3       10400
flood1  .pivot.y4                   10400
flood2  .flood.y1       61000
flood2  .flood.y2                   61000
flood2  .flood.y3                               61000
flood2  .flood.y4                                           61000
flood2  .pivot.y3       12400
flood2  .pivot.y4                   12400

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----     769 PARAMETER dlp_cur_salvage  DLP - current salvage values

                           y1

pivot1.pivot.y2          2400
pivot2.pivot.y1          4400
pivot4.pivot.y2          8400


----     777 PARAMETER dlp_cur_prodincome  DLP - current production income

INDEX 1          = farm1

                                       y1

pivot1.pivot.m1.cropB.y1            16000
pivot1.pivot.m1.cropB.y2            18000
pivot2.pivot.m1.cropB.y1            18000

INDEX 1          = farm2

                                       y1

pivot4.pivot.m1.cropB.y1            16000
pivot4.pivot.m1.cropB.y2            18000


----     785 PARAMETER dlp_cur_operating  DLP - current operating capital
```

```
                                              y1

pivot1.pivot.m1.cropB.y1                    1222
pivot1.pivot.m1.cropB.y2                    1223
pivot2.pivot.m1.cropB.y1                    2223
pivot4.pivot.m1.cropB.y1                    4222
pivot4.pivot.m1.cropB.y2                    4223


----     794 PARAMETER dlp_cur_sys_networth  DLP - current irri system net
worth

                            y1

pivot1.pivot.y1           5600
pivot1.pivot.y2           2400
pivot2.pivot.y1           4400
pivot4.pivot.y1          19600
pivot4.pivot.y2           8400

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----    805 PARAMETER dlp_cur_taxdep  DLP - current depreciation deduction

                            y1

pivot1.pivot.y2           3600
pivot1.pivot.y3           2400
pivot2.pivot.y3           4400
pivot4.pivot.y2          12600
pivot4.pivot.y3           8400


----     815 PARAMETER t_plus_crop  number of crop years past the planning
horizon

                  y3          y4

cropB         1.000       2.000


----    823 PARAMETER t_plus_inv  number of investment years past the planning
horizon

                  y3          y4

pivot         1.000       2.000


----     831 PARAMETER t_plus_pay  number of payment years past the planning
horizon

y3 1.000,    y4 2.000


----    853 PARAMETER t_plus_crop_pv  present value of crop gross margin

                                              y3          y4

farm1.dryland1.flood.m1.cropB          -819588    -1580669
farm1.dryland1.pivot.m1.cropB         -1499678    -2894459
farm1.pivot1  .pivot.m1.cropB         -7597883   -14694353
farm1.pivot2  .pivot.m1.cropB        -38756201   -74961378
farm1.pivot3  .pivot.m1.cropB        -23663154   -45772774
farm2.pivot4  .pivot.m1.cropB        -97318070  -188248359
farm2.flood1  .flood.m1.cropB        -92065756  -178092415
farm2.flood1  .pivot.m1.cropB        -92222481  -178393715
```

```
farm2.flood2  .flood.ml.cropB   -113472223  -219504366
farm2.flood2  .pivot.ml.cropB   -113656986  -219859907


----     867 PARAMETER t_plus_sal_pv  present value of salvage

                              y3          y4

dryland1.pivot               374         349
pivot1  .pivot              2243        2096
pivot2  .pivot              4112        3843
pivot3  .pivot              5981        5590
pivot4  .pivot              7850        7337
flood1  .pivot              9720        9084

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         867 PARAMETER t_plus_sal_pv  present value of salvage

                              y3          y4

flood2  .pivot             11589       10831


----     881 PARAMETER t_plus_dep_pv  present value of depreciation

                              y3          y4

dryland1.pivot               374         910
pivot1  .pivot              2243        5461
pivot2  .pivot              4112       10011
pivot3  .pivot              5981       14562
pivot4  .pivot              7850       19113
flood1  .pivot              9720       23663
flood2  .pivot             11589       28214


----     903 PARAMETER t_plus_pay_pv  present value of payments

                              y3          y4

farm1.interest      6.145661E-2 1.714197E-1
farm1.principal     3.615095E-1 6.468417E-1
farm2.interest      6.145661E-2 1.714197E-1
farm2.principal     3.615095E-1 6.468417E-1


----     925 PARAMETER annuity_crop  after tax annuity of crop gross margin

                                          y3          y4

farm1.dryland1.flood.ml.cropB      -30534994   -28537378
farm1.dryland1.pivot.ml.cropB      -55982337   -52319941
farm1.pivot1  .pivot.ml.cropB     -284675711  -266052066
farm1.pivot2  .pivot.ml.cropB    -1452368784 -1357354004
farm1.pivot3  .pivot.ml.cropB     -886922464  -828899499
farm1.pivot4  .pivot.ml.cropB    -3648204424 -3409536845
farm1.flood1  .flood.ml.cropB    -3451352646 -3225563221
farm1.flood1  .pivot.ml.cropB    -3456736686 -3230595034
farm1.flood2  .flood.ml.cropB    -4253864041 -3975573870
farm1.flood2  .pivot.ml.cropB    -4260299209 -3981588046
farm2.dryland1.flood.ml.cropB      -30952287   -28927371
farm2.dryland1.pivot.ml.cropB      -56517983   -52820545
farm2.pivot1  .pivot.ml.cropB     -285233154  -266573041
farm2.pivot2  .pivot.ml.cropB    -1452926227 -1357874979
farm2.pivot3  .pivot.ml.cropB     -887479907  -829420474
farm2.pivot4  .pivot.ml.cropB    -3647646981 -3409015870
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```
farm2.flood1  .flood.m1.cropB  -3450935353 -3225173227
farm2.flood1  .pivot.m1.cropB  -3456736686 -3230595034
farm2.flood2  .flood.m1.cropB  -4253446748 -3975183877
farm2.flood2  .pivot.m1.cropB  -4260299209 -3981588046

CanalNetwork.gms
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E        x        e        c        u        t        i        o        n
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----     938 PARAMETER annuity_sal  annuity of salvage

                          y3          y4

dryland1.pivot          4359        4074
pivot1   .pivot        26156       24445
pivot2   .pivot        47953       44816
pivot3   .pivot        69750       65187
pivot4   .pivot        91547       85558
flood1   .pivot       113344      105929
flood2   .pivot       135141      126300

----     951 PARAMETER annuity_dep  annuity of depreciation

                          y3          y4

dryland1.pivot         23834       22275
pivot1   .pivot       143004      133648
pivot2   .pivot       262173      245022
pivot3   .pivot       381343      356395
pivot4   .pivot       500513      467769
flood1   .pivot       619682      579142
flood2   .pivot       738852      690516

----     973 PARAMETER annuity_pay  annuity of payment

                          y3          y4

farm1.interest             4           4
farm1.principal           12          11
farm2.interest             4           4
farm2.principal           12          11
```

APPENDIX **B**

RISK SIMULATION MODULE

```
*-----------------------------------------------------------------------------
*   MODEL:        CumRisk.GMS
*
*   PROGRAMMER:  Bennie Grove
*                Researcher
*                Department of Agricultural Economics
*                University Orange Free State, Bloemfontein, South Africa
*
*  DESCRIPTION:  Procedures to draw correlated prices and yields from multivariate
*                cumulative probability distributions
*-----------------------------------------------------------------------------

*=== Define the sets ==========================================================
SET        R        random numbers /1*100/
           i       correlated entities / wheat,maize,g_nuts /
           PE       probability and empirical /PROB,EMP,TRI /
           RL        all the row labels for empirical input data /MIN,OBS1*OBS50,MAX
/
           MM(RL)  minimum maximum /MIN,MAX /
           O(RL)   empirical observations /OBS1*OBS15/
           IL       parameters used to interpolate / Pi,Pi1,Xi,Xi1 /
           T        time /y1*y15/
           itype(pe,i)  mapping  correlated  entities  to  type  of  inputs  /
tri.wheat,tri.maize,tri.g_nuts /
           m     management option / m1*m256/
p  production possibilities
   /flood
    pivot/

;
ALIAS(i,J,K,st,st1);
ALIAS(O,O1);
ALIAS(T,IT,MT);
ALIAS(m,m1);
ALIAS(p,p1);
ALIAS(R,rnd);


*=== Initialise the parameters-------------------------------------------------
PARAMETER V(I,J)      Correlation matrix
```

```
          C(I,J)      Cholesky decomposition of V
          VC(I,J)     cc'=V
          WB(I,J)     Whistle blower check matrix
          ISND(I,R,t)  Independant standard normal deviates
          CSND(R,I,t)  Correlated standard normal deviates
          CUD (R,I,t)  Correlated uniformly distributed random numbers
          DATA(m,p,RL,PE,I)  Emperical  values  used  to  construct  the  probability
distribution
          SORT(RL,PE,I) Table initialised to sort empirical observed values
          CP(O,PE,I)  Cumalative probability
          N(I)        Number of empirical observations
          EMIN(PE,I) Empirical minimum value
          EMAX(PE,I) Empirical maximum value
          PEMAX(I)     Probability of the empirical maximum value
          SORTMIN(PE,I) Minimum of the sorted observed values
          CUMPAR(R,IL,I,t)  Parameters used to interpolate
          FX(R,I,p,m,t) Correlated random yield and prices
          AUTOCOR(i)   autocorrelation lag 1
          IV(I,t,it)
          IC(I,T,it)
          IVC(I,t,it)    intertemporal cc'=V
          IWB(I,t,it)    intertemporal Whistle blower check matrix
          ACSND(R,I,t)  uato correlated standard normal deviates

;

SCALAR SMALL / 0.01 /;

*=== Enter the correlation matrix ============================================
   TABLE V(I,J)

        wheat                 maize            g_nuts
wheat   1
maize   0.593173207     1
g_nuts  0.848690355     0.376086529     1
*4      -0.203276079    -0.017227116    0.111536035     1
;

*  Create upper triangular of correlation matrix
   V(I,J) $ (NOT V(I,J)) = V(J,I);

*  Create lower triangular of correlation matrix
*   V(J,I) $ (NOT V(J,I)) = V(I,J);

DISPLAY V;

parameter AUTOCOR(i)
/
wheat    0.200630035
maize   -0.167656037
g_nuts   0.320539994
```

```
*4      -0.850214978
/
;


IV(I,T,IT)$(ord(t)=ord(it)) =1;
*IV(I,T,it)$(not sameas(t,it))=autocor(i);
IV(I,T,it)$(ord(t)=ord(it)+1)=autocor(i);
*  Create upper triangular of correlation matrix
   IV(I,T,IT) $ (NOT IV(I,T,IT)) = IV(I,IT,T);

display iv;
parameter complete(t,i,it,j);
complete(t,i,it,j)$sameas(t,it)=  V(I,J);
complete(t,i,it,j)$sameas(i,j)=  IV(I,T,IT);

options complete :2:2:2;
display complete;

*=== Decompose correlation matrix using cholesky factorisation
*     Source: Principles of random variate generation
*             John Dagpunar (1988)
*             Pages 157-158 =====================================================

*   C("1","1") = SQRT(V("1","1"));
   C(i,j)$(ord(i)=1 and ord(j)=1)= SQRT(V(i,j));


*   LOOP( J $ (ORD(J) > 1), C(J,"1") = V("1",J)/C("1","1") );
*   when you use the decompose the correlation matrix the value of C("1","1") will
always equal 1

   LOOP((i, J) $( (ORD(J) > 1) and ord(i)=1), C(J,i) = V(i,J)/1 );

   LOOP(I $(ORD(I)>1),
        C(I,I) = SQRT( V(I,I) - SUM(K $(ORD(K) < ORD(I)), SQR(C(I,K))))
                 $((V(I,I) - SUM(k $(ORD(k) < ORD(I)), SQR(C(I,K))))>0);
        LOOP(J $(ORD(J) > ORD(I)),
        C(J,I) = ((V(I,J) - SUM(k $ (ORD(k) < ORD(I)), C(I,k)*C(J,k)))/C(I,I))
                 $(C(I,I)> 0);
              );
        );
*  Print out
   DISPLAY C;

*=== Check the decomposition matrix CC'=V ======================================

*  Sum over both the colomns, m, and not over colomn row because you multiply
*  with the transpose of C
   VC(I,J) = SUM(k, C(I,k)*C(J,k));
*  Print out
```

```
   DISPLAY VC;

*  Whistle Blower check of the decomposition matrix
*  Note: Values should equal 0
   WB(I,J)=V(I,J)-VC(I,J);
*  Print out
   DISPLAY WB;

*_______________________________________________________________________
*=== Decompose correlation matrix using cholesky factorisation
*    Source: Principles of random variate generation
*            John Dagpunar (1988)
*            Pages 157-158 =====================================================

   IC(i,"y1","y1") = SQRT(IV(i,"y1","y1"));

*   LOOP( T $ (ORD(T) > 1), IC(i,T,"1") = IV(i,"1",T)/IC(i,"1","1"); );
*   when you use the decompose the correlation matrix the value of IC(i,"1","1")
will always equal 1
   LOOP((it, T) $ (ORD(T) > 1 and ord(it)=1), IC(i,T,it) = IV(i,it,T)/1 );

   LOOP(IT $(ORD(IT)>1),
        IC(i,IT,IT)  =  SQRT(  IV(i,IT,IT)  -  SUM(MT  $(ORD(MT)  <  ORD(IT)),
SQR(IC(i,IT,MT))))
                  $((IV(i,IT,IT)    -    SUM(MT    $(ORD(MT)    <    ORD(IT)),
SQR(IC(i,IT,MT))))>0);

        LOOP(T $(ORD(T) > ORD(IT)),
        IC(i,T,IT)  =  ((IV(i,IT,T)  -  SUM(MT  $  (ORD(MT)  <  ORD(IT)),
IC(i,IT,MT)*IC(i,T,MT)))/IC(i,IT,IT))
                  $(IC(i,IT,IT)> 0);
                );
        );
*  Print out
   OPTION ic :6:2:1;
   DISPLAY IC;

*=== Check the decomposition matrix CC'=V ==================================

*  Sum over both the columns, m, and not over column row because you multiply
*  with the transpose of C
   IVC(I,t,it) = SUM(Mt, IC(i,t,Mt)*IC(i,it,Mt));
*  Print out
   DISPLAY IVC;

*  Whistle Blower check of the decomposition matrix
*  Note: Values should equal 0
   IWB(I,t,it)=IV(I,t,it)-IVC(I,t,it);
*  Print out
   DISPLAY IWB;
*_______________________________________________________________________
```

```
*$ontext
*=== Generate correlated random number used in risk simulation ================

* Generate independant standard normal deviates equal to number of iterations
  ISND(I,R,t) = NORMAL(0,1);
* Print out
  DISPLAY ISND;

* Correlate standard normal deviates
  CSND(R,I,t) =  SUM(J, C(I,J)*ISND(J,R,t));
* Print out
  DISPLAY CSND;

* Auto-Correlate standard normal deviates
  ACSND(R,I,t) =  SUM(it, IC(I,T,it)*CSND(R,I,it));
* Print out
  options ACSND :4:2:1;
  DISPLAY ACSND;







* Integrate area under the normal distribution to make it uniformly distributed
* Note: These are the correlated random numbers used in the risk simulation
  CUD(R,I,t) = ERRORF(ACSND(R,I,t));
*  CUD(R,I,t) = ERRORF(CSND(R,I,t));

* Print out
options cud:2:1:2;
  DISPLAY CUD;
*$ONTEXT
execute_unload "cud",cud;
*=== Input data to generate probability distribution tables used in
*    the risk simulation ================================================

* Note: for the triangular distribution
*       obs1 = minimum, obs2 = most likely, obs3 = maximum

*  TABLE DATA(m,p,RL,PE,I)
$INCLUDE riskdata.gms
;
*****************************************************************************
*                          TRIANGULAR DISTRIBUTION
*****************************************************************************
*  assign value to fx if the random number is <= the critical value
   FX(Rnd,I,p,m,t)
          $(
            itype("tri",i)
            and
```

```
              CUD(rnd,I,t)LE ((DATA(m,p,"obs2","tri",I)-DATA(m,p,"obs1","tri",I))
                            /((DATA(m,p,"obs3","tri",I)-
DATA(m,p,"obs1","tri",I))+0.1))
              )
         =    DATA(m,p,"obs1","tri",I)
                +sqrt(
                     CUD(Rnd,I,t)
                    *(DATA(m,p,"obs3","tri",I)-DATA(m,p,"obs1","tri",I))
                    *(DATA(m,p,"obs2","tri",I)-DATA(m,p,"obs1","tri",I))
                     );
*   assign value to fx if the random number is > the critical value
   FX(Rnd,I,p,m,t)
           $(
              itype("tri",i)
              and
              CUD(Rnd,I,t)> ((DATA(m,p,"obs2","tri",I)-DATA(m,p,"obs1","tri",I))
                            /((DATA(m,p,"obs3","tri",I)-
DATA(m,p,"obs1","tri",I))+0.1))
              )
         =    DATA(m,p,"obs3","tri",I)
              -sqrt(
                    (1-CUD(Rnd,I,t))
                   *(DATA(m,p,"obs3","tri",I)-DATA(m,p,"obs1","tri",I))
                   *(DATA(m,p,"obs3","tri",I)-DATA(m,p,"obs2","tri",I))
                    );

*  Print fx with 2 decimals, first set in row and next two sets in the column
   options fx :4:1:2;
   DISPLAY fx;
parameter meanfx(I,p,m,t)
          stdev(I,p,m,t)
          COVAR(i,p,m,T,j,p1,m1,it)
          cv(I,p,m,t);

meanfx(I,p,m,t)=sum(rnd,FX(Rnd,I,p,m,t))/card(rnd);
stdev(I,p,m,t)$(sum(rnd,FX(Rnd,I,p,m,t)))
                    = SQRT(
                       (CARD(rnd)*SUM(rnd,SQR(FX(Rnd,I,p,m,t)))-
SUM(rnd,FX(Rnd,I,p,m,t))**2)
                              /
                       (CARD(rnd)*(CARD(rnd)-1))
                       );
cv(I,p,m,t)$stdev(I,p,m,t)= stdev(I,p,m,t)/(meanfx(I,p,m,t)+0.1);

$ontext

*COVAR(i,pf,m,T,j,pf1,m1,it)$meanfx(I,pf,m,t)        =       SUM((r),(FX(R,I,pf,m,t)-
meanfx(I,pf,m,t))*(FX(R,j,pf1,m1,it)-meanfx(j,pf1,m1,it)))/(CARD(r)-1);
COVAR(st,p,m,T,st1,p1,m1,it)
                                  $(complete(t,st,it,st1)
                                    and
```

```
                                    stdev(st,p,m,t))

=complete(t,st,it,stl)*stdev(st,p,m,t)*stdev(stl,pl,ml,it);
options meanfx :0:3:1;
options stdev :0:3:1;
options covar :0:4:4;
options cv :0:3:1;
*display meanfx,stdev,cv,covar;
$offtext
*execute_unload "cor_COVAR",covar ;
execute_unload "fx_for_motad",FX;
execute_unload "mean",meanFX;
execute_unload "CV",CV;


$ontext
```

APPENDIX **C**

ENTERPRISE BUDGET

WHEAT CENTRE PIVOT 2003

Item	Unit	Price per Unit	Quantity	Value per ha
Gross Income:				
*Wheat	ton	1200	6.5	7800.00
Total				7800.00
Opperating Costs: Area Dependant				
Seed	kg	6.36	100	636.00
7:2:3(31) + Zn	kg	2.49	500	1245.00
KAN (28)	kg	1.67	350	584.50
Omniboost	kg	12.98	5	64.90
K P Max	liter	7.70	1	7.70
10:1:6(20) liquid	kg	1.53	190	290.70
Buctril DS	liter	145.00	1	145.00
MCPA	liter	51.00	0.5	25.50
Metasystox	liter	117.00	0.5	58.50
Parathion	liter	92.00	0.65	59.80
Granate EC	liter	193.68	0.7	135.58
Crop dusting	ha	95.00	2	190.00
Total				3443.18
Opperating Costs: Yield Dependant				
Contract Harvesting				715.00
Contract Transport				114.00
Total				829.00
Opperating Costs: Other				
*Irrigation	mm.ha	1.61	0	0.00
Fuel	l	2.70	91.2	364.80
Reparations	R	2.70	10% of fuel	36.48
Lubricant	R	2.70	2% of fuel	7.30
Insurance	R	575.25	5.9%	575.25
Labour	mandays	43.20	0.98	42.34
Interest	R	279.04	1	279.04
Total				1305.20
^Total Operating Costs				**5577.38**
^Gross Margin				**2222.62**

* Variables changed during optimisation to indicate the effect of different irrigation strategies on the Gross Margin

^Cost of water excluded.

WHEAT: FLOOD				2003
Item	Unit	Price per Unit	Quantity	Value per ha
Gross Income:				
*Wheat	ton	1200	5.7	6840.00
Total				6840.00
Opperating Costs: Area Dependant				
Saad	kg	6.36	100	636.00
7:2:3(31) + Zn	kg	2.49	500	1245.00
KAN (28)	kg	1.67	350	584.50
Omniboost	kg	12.98	5	64.90
K P Max	liter	7.70	1	7.70
10:1:6(20) vloeibaar	kg	1.53	0	0.00
Buctril DS	liter	145.00	1	145.00
MCPA	liter	51.00	0.5	25.50
Metasystox	liter	117.00	0.5	58.50
Parathion	liter	92.00	0.65	59.80
Granate EC	liter	193.68	0.7	135.58
Crop Dusting	ha	95.00	2	190.00
Total				3152.48
Opperating Costs: Yield Dependant				
Contract Harvesting				627.00
Contract Transport				110.00
Total				737.00
Opperating Costs: Other				
*Irrigation	mm.ha	0.81	0	0.00
Fuel	l	2.70	92	364.80
Reparations	R	2.70	10% of fuel	36.48
Lubricant	R	2.70	2% of fuel	7.30
Insurance	R	504.45	5.9%	504.45
Labour	mandays	36.60	11	402.60
Interest	R	246.43	1	246.43
Total				1562.06
^Total Operating Costs				**5451.53**
^Gross Margin				**1388.47**

* Variables changed during optimisation to indicate the effect of different irrigation strategies on the Gross Margin

^Cost of water excluded.

MAIZE: CENTRE PIVOT				2003
Item	**Unit**	**Price per Unit**	**Quantity**	**Value per ha**
Gross Income:				
*Maize	ton	700.00	12	8400.00
Total				8400.00
Opperating Costs: Area Dependant				
Seed	kg	36.00	25	900.00
7:2:3 (31) + 0.5% Zn	kg	2.22	500	1110.00
KAN	kg	1.67	400	668.00
Crop Dusting	ha	105.00	1	105.00
Omniboost	kg	12.58	5	62.90
Omnispoor	kg	61.81	1	61.81
Guardian	liter	106.00	1	106.00
Cruiser	liter	1339.00	0.25	334.75
Monokrotofos	liter	66.00	0.75	49.50
Total				3397.96
Opperating Costs: Yield Dependant				
Contract Harvesting				780.00
Contract Transport				240.00
Total				1020.00
Opperating Costs: Other				
*Irrigation	mm.ha	1.61	0	0.00
Fuel	l	2.70	104	280.80
Reparations	R	2.70	10% of fuel	28.08
Lubricant	R	2.70	2% of fuel	5.62
Insurance	R	300.00	2.50%	300.00
Labour	mandays	43.20	1.1	49.26
Interest	R	287.96	1	287.96
Total				951.72
^Total Operating Costs				**5369.68**
^Gross Margin				**3030.32**

* Variables changed during optimisation to indicate the effect of different irrigation strategies on the Gross Margin

^Cost of water excluded.

MAIZE: FLOOD				2003
Item	Unit	Price per Unit	Quantity	Value per ha
Gross Income:				
*Maize	ton	700.00	8	5600.00
Total				5600.00
Opperating Costs: Area Dependant				
Seed	kg	36.00	25	900.00
7:2:3 (31) + 0.5% Zn	kg	2.22	500	1110.00
KAN	kg	1.67	350	584.50
Crop Dusting	ha	105.00	0	0.00
Omniboost	kg	12.58	5	62.90
Omnispoor	kg	61.81	1	61.81
Guardian	liter	106.00	1	106.00
Cruiser	liter	1339.00	0.25	334.75
Monokrotofos	liter	66.00	0.75	49.50
Total				3209.46
Opperating Costs: Yield Dependant				
Contract Harvesting				780.00
Contract Transport				240.00
Total				1020.00
Opperating Costs: Other				
*Irrigation	mm.ha	0.81	0	0.00
Fuel	l	2.70	104	280.80
Reparations	R	2.70	10% of fuel	28.08
Lubricant	R	2.70	2% of fuel	5.62
Insurance	R	180.00		180.00
Labour	mandays	36.60	9.1	333.06
Interest	R	287.96	1	287.96
Total				1115.52
^Total Operating Costs				**5344.98**
^Gross Margin				**255.02**

* Variables changed during optimisation to indicate the effect of different irrigation strategies on the Gross Margin

^Cost of water excluded.

GROUNDNUTS CENTRE PIVOT				2003
Item	**Unit**	**Price per Unit**	**Quantity**	**Value per ha**
Gross Income:				
*Groundnuts	ton	3146.72	3.5	11013.53
Total				11013.53
Opperating Costs: Area Dependant				
Seed	kg	10.00	150	1500.00
Nitrogen	kg	5.40	120	648.00
Phosphate	kg	11.95	25	298.75
Potasium	kg	4.68	20	93.60
Molibdaat	kg	98.73	0.25	24.68
Brnx	kg	38.13	1	38.13
Karate	liter	298.42	0.13	38.79
Folicur	liter	235.93	0.9	212.34
Sanacarb	kg	54.00	10.5	567.00
Hammer	liter	538.60	0.3	161.58
Relay	liter	54.00	10.5	567.00
Total				4149.87
Opperating Costs: Yield Dependant				
Harvest by hand	mandays	36.60	33	1207.80
Contract Transport	ton	50.00	3.5	175.00
Total				1382.80
Opperating Costs: Other				
*Irrigation	mm.ha	1.61	0	0.00
Fuel	l	2.70	130	351.00
Reparations	R	2.70	10% of fuel	35.10
Lubricant	R	2.70	2% of fuel	7.02
Labour	mandays	43.20	6	259.20
Interest	R	235.82	1	235.82
Total				888.14
^Total Operating Costs				**6420.81**
^Gross Margin				**4592.72**

* Variables changed during optimisation to indicate the effect of different irrigation strategies on the Gross Margin

^Cost of water excluded.

GROUNDNUTS: FLOOD				2003
Item	Unit	Price per Unit	Quantity	Value per ha
Gross Income:				
*Groundnuts	ton	3146.72	3	9440.17
Total				9440.17
Opperating Costs: Area Dependant				
Seed	kg	10.00	150	1500.00
KAN	kg	1.67	200	334.00
X plode	kg	30.15	5	150.75
Omniboost	kg	12.58	8	100.64
Molyflow + T	kg	29.75	1.2	35.70
Score	kg	590.00	0.6	354.00
Punch	liter	350.63	0.3	105.19
Cropguard	liter	19.10	40	764.00
Monochrotofos	liter	66.00	0.75	49.50
Thiulin	60g	15.85	3	47.55
				0.00
Total				3441.33
Opperating Costs: Yield Dependant				
Harvest by hand	mandays	36.60	33	1207.80
Contract Transport	ton	50.00	3.5	175.00
Total				1382.80
Opperating Costs: Other				
*Irrigation	mm.ha	0.81	0	0.00
Fuel	l	2.70	130	351.00
Reparations	R	2.70	10% of fuel	35.10
Lubricant	R	2.70	2% of fuel	7.02
Labour	mandays	36.60	16.5	603.90
Interest	R	235.82	1	235.82
Total				1232.84
^Total Operating Costs				**6056.97**
^Gross Margin				**3383.20**

* Variables changed during optimisation to indicate the effect of different irrigation strategies on the Gross Margin

^Cost of water excluded.

LUCERNE: FLOOD				2003
Item	Unit	Price per Unit	Quantity	Value per ha
Gross Income:				
*Lucerne	ton	800.00	19	15200.00
Total				15200.00
Opperating Costs: Area Dependant				
2:3:4(30)+Zn	kg	2.29	300	687.00
Omniboost	kg	12.58	10	125.80
Kelp-P-Max	l	29.07	4	116.28
Galant Super	l	228.80	0.5	114.40
Karate	l	244.00	0.3	73.20
Folimat	l	280.00	0.075	21.00
Casual Labour	mandays	33.00	10	330.00
Total				1467.68
Opperating Costs: Yield Dependant				
Baling wire	bale	0.28	760	212.80
Contract Transport				494.00
Total				706.80
Opperating Costs: Other				
*Irrigation	mm.ha	0.81	0	0.00
Fuel	l	2.70	138.1	372.87
Reparations	R	2.70	10% of fuel	13.81
Lubricant	R	2.70	2% of fuel	2.76
Labour	mandays	36.6	17	622.20
Interest				1011.64
^Total Operating Costs				**3186.12**
^Gross Margin				**12013.88**

* Variables changed during optimisation to indicate the effect of different irrigation strategies on the Gross Margin

^Cost of water excluded.

COTTON: CENTRE PIVOT				2003
Item	Unit	Price per Unit	Quantity	Value per ha
Gross Income:				
*Cotton	ton	3500	4	14000.00
Total				14000.00
Opperating Costs: Area Dependant				
Seed	kg	10.08	10	100.80
Nitrogen	kg	5.40	170	918.00
Phosphate	kg	11.95	40	478.00
Potasium	kg	4.68	80	374.40
Gluco-Zinc	l	25.00	1	25.00
Liquid boron	l	13.77	1	13.77
Lignofeed ZMC	l	27.00	2	54.00
3:08:15	l	16.10	20	322.00
Treflan	l	44.50	2	89.00
Decis	l	180.00	0.215	38.70
Temik	kg	100.54	2	201.08
Folimat	l	154.00	0.2	30.80
Thioflo	l	51.95	2.75	142.86
Pix	l	121.40	0.375	45.53
Effon	l	53.31	0.5	26.66
Bladval	l	23.28	10	232.80
Crop Dusting	ha	85	9	765.00
Total				3858.39
Opperating Costs: Yield Dependant				
Contract Harvesting				1200.00
Contract Transport	R/ton/km	1.80		144.00
Total				1344.00
Opperating Costs: Other				
*Irrigation	mm.ha	1.61	0	0.00
Fuel	l	2.70	114.63	309.50
Labour	R	2.70	10% of fuel	30.95
Lubricant	R	2.70	2% of fuel	6.19
Insurance	R	17%		2100.00
Labour	mandays	36.60	31.3	1145.58
Levy		2.5%		350.00
Interest	R	274.20	1	0.00
Total				3942.22
^Total Operating Costs				**9144.61**
^Gross Margin				**4855.39**

* Variables changed during optimisation to indicate the effect of different irrigation strategies on the Gross Margin

^Cost of water excluded.

COTTON: FLOOD				2003
Item	Unit	Price per Unit	Quantity	Value per ha
Gross Income:				
*Cotton	ton	3500	3.5	12250.00
Total				12250.00
Opperating Costs: Area Dependant				
Seed	kg	10.08	25	252.00
3:2:4(31)+Zn	kg	2.76	400	1104.00
KAN(28)	kg	1.97	400	788.00
Omniboost	kg	12.77	5	63.85
Xtra-Cal	l	25.20	3	75.60
Liquid boron	l	13.77	0	0.00
Lignofeed ZMC	l	27.00	0	0.00
3:08:15	l	16.10	0	0.00
Treflan	l	44.50	1	44.50
Decis	l	180.00	0	0.00
Temik	kg	44.50	7.5	333.75
Folimat	l	154.00	0	0.00
Thioflo	l	51.95	2.75	142.86
Pix	l	121.40	0.375	45.53
Baythroid	l	200	0.4	80.00
Bladval	l	23.28	10	232.80
Crop Dusting	ha	85	2	170.00
Total				3332.89
Opperating Costs: Yield Dependant				
Contract Harvesting				1200.00
Contract Transport	R/ton/km	1.80		126.00
Total				1326.00
Opperating Costs: Other				
*Irrigation	mm.ha	0.81	0	0.00
Fuel	l	2.70	136.5	368.55
Labour	R	2.70	10% of fuel	36.86
Lubricant	R	2.70	2% of fuel	7.37
Insurance	R	17%		2100.00
Labour	mandays	36.60	38.8	1420.08
Levy		2.5%		306.25
Interest	R	274.20	1	0.00
Total				4239.11
^Total Operating Costs				**8897.99**
^Gross Margin				**3352.01**

* Variables changed during optimisation to indicate the effect of different irrigation strategies on the Gross Margin

^Cost of water excluded.

APPENDIX D

SKELETON MODEL INPUT PARAMETERS

```
*------------------------------------------------------------------------------
*DOMAIN OF THE MODELS
*------------------------------------------------------------------------------
SETS
g  geographical information identifiers
   /
4b4_6b4
1b4_3b4


4b4_6b4_dam

5c1_5c3_off
5c4_5c6_off
/
pg(g)  geographical areas related to crop production
   /
4b4_6b4
1b4_3b4


/
ig(g)  geographical areas related to irrigation production
   /
4b4_6b4
1b4_3b4


/
ws(g)  geographical irrigation water source identifiers
   /
4b4_6b4_dam

5c1_5c3_off
5c4_5c6_off

/
pws(ws)  geographical primarary irrigation water source identifiers
   /
```

```
5c1_5c3_off
5c4_5c6_off

/
off(ws) all water abstraction offtakes from conveyance structure
   /
5c1_5c3_off
5c4_5c6_off

/
dam(ws) all farm dam storage identifiers
   /
4b4_6b4_dam

/
*bore(ws) all boreholes identifyers
*   /    borehole1  /


f  farms
   /
farm27
farm32
/
c  crops
   /
pecan
lucerne
maize
g_nuts
wheat
/
st(c) cash crops
   /
maize
g_nuts
wheat
   /
m  management alternatives
    /m1*m256/
r  alternative resource uses - excluding irrigation
    /labour, tractor/
t  years in planning period
   /y1*y15 /
wt time periods within t to specify water demand
   /wt1*wt52/
l  alternative interest rates
   /borrow_ope, borrow_inv, invest_bank/
p  production possibilities
```

```
   /flood
    pivot/
*dry(p)  dryland production possibilities
*   /
*   /
irri(p)  irrigation production possibilities
   /flood
    pivot/
rnd simulated states of nature
   /1*100/
con  all conveyance identifiers
   /
    1con_nc              primary conceyance
    2con_tvv5            secondary conveyance
    3con_5c              tertiary conveyance
/

prim(con) primarary conveyance identifiers
   /
    1con_nc              primary conceyance
/
sec(con) second level of conveyance structures
   /
    2con_tvv5            secondary conveyance
/
ter(con) tertiary conveyance identifiers
   /
    3con_5c              tertiary conveyance
/
;
ALIAS (t,pt,it)
ALIAS (c,c1)
ALIAS (st,st1,i)
ALIAS (pg,pg1)
ALIAS (p,p1)
ALIAS (m,m1)
ALIAS (con,con1,con2)
ALIAS (irri,irri1);

*==========================================================================
*DATA INPUT: Water supply
*==========================================================================
TABLE
prim_to_sec(con,con1) link primarary to secondary conveyance
          2con_tvv5
1con_nc           1
;
*-------------------------------------------------------------------------
TABLE
```

```
sec_to_ter(con,con1) link secondary to tertiary conveyance
            3con_5c
2con_tvv5         1
;
*______________________________________________________________________________
PARAMETER
con_to_con(con,con1,con2) link primarary to secondary to tersiary conveyance;
con_to_con(con,con1,con2)= prim_to_sec(con,con1)*sec_to_ter(con1,con2);
option con_to_con :0:2:1;
display con_to_con;
*______________________________________________________________________________
TABLE
con_to_off(con,off) link conveyance to offtakes
           5c1_5c3_off  5c4_5c6_off
3con_5c    1            1
;
*______________________________________________________________________________
TABLE
pg to ws(pg,ws) link production area to primarary water supply source
           5c1_5c3_off  5c4_5c6_off  4b4_6b4_dam
1b4_3b4    1
4b4_6b4                 1            1
;
*______________________________________________________________________________
TABLE
dam_to_ws(dam,ws)    link dam storage to offtake or borehoe at water supply
source
               5c4_5c6_off
4b4_6b4_dam    1
;
*______________________________________________________________________________
TABLE
pg_to_f(pg,f) link farm to production areas
           farm27   farm32
1b4_3b4    1
4b4_6b4             1
;
*______________________________________________________________________________
PARAMETER
f_to_ws(f,ws) link farm to water source;
f_to_ws(f,ws)=sum(pg,pg_to_f(pg,f)*pg_to_ws(pg,ws));
display f_to_ws;
*______________________________________________________________________________
PARAMETER
concap(con) conveyance capacity - m3 per time period wt
/
1con_nc    999999
2con_tvv5  999999
3con_5c    10800
```

```
/
;
concap(con)=concap(con)*5.5
*concap is multiplied with 5.5 since sytem is operated for 5.5 days per week
;
*______________________________________________________________________________
TABLE
wsirri_cap(ws,irri) maximum irrigation capacity - m3 per time period wt
                 flood   pivot
5c1_5c3_off      10800   7848
5c4_5c6_off      10800   7848
4b4_6b4_dam      17200   16336
*$include "!wscap.txt"
;
wsirri_cap(ws,irri)=wsirri_cap(ws,irri)*7;
*______________________________________________________________________________
PARAMETER
wscap(ws) maximum abstraction capacity from  offtake - m3 per time period wt
/
5c1_5c3_off      10800
5c4_5c6_off      10800
/
;
wscap(ws)=wscap(ws)*5.5;
*wscap is multiplied with 5.5 since sytem is operated for 5.5 days per week
*______________________________________________________________________________
TABLE
damwscap(dam,ws) maximum abstraction capacity to dam - m3 per time period wt
               5c4_5c6_off
4b4_6b4_dam    7200
;
damwscap(dam,ws)=damwscap(dam,ws)*7
;
*______________________________________________________________________________
PARAMETER
damcap(dam) storage capacity of dam - m3
/
4b4_6b4_dam     7200
/
;
*______________________________________________________________________________
TABLE
level_ini(dam,wt,t) initial dam level - m3
                        y1
4b4_6b4_dam.wt1         7200

;
*==============================================================================
*DATA INPUT: Resource availability and use
```

```
*=============================================================================
TABLE
pg_to_p(pg,p) link production areas to production possibilities
           flood   pivot
1b4_3b4    1       1
4b4_6b4    1       1
;
*_____________________________________________________________________________
TABLE
c_to_p(c,p) link crop to irrigation production possibilities
                   flood      pivot
pecan                  1
lucerne                1          1
maize                  1          1
g_nuts                 1          1
wheat                  1          1
;
*_____________________________________________________________________________
PARAMETER
areas(pg) hectares of each production area - ha
/
1b4_3b4    76
4b4_6b4    76
/
;
*_____________________________________________________________________________
TABLE
cur_irri_ha(pg,p) current production possibilities - ha
           flood   pivot
1b4_3b4    76
4b4_6b4    40      36
;
*_____________________________________________________________________________
TABLE
cur_crops_ha(pg,p,m,c) hectares of current crop production - last year is year
                             pecan
1b4_3b4       .flood .m1
4b4_6b4       .flood .m1     35
;
*_____________________________________________________________________________
TABLE
cur_irri_cycle(pg,irri) years of investment - begining of year
           flood   pivot
1b4_3b4
4b4_6b4            3
;
*_____________________________________________________________________________
TABLE
cur_crop_cycle(pg,c) years of current crop production - beginning of year
```

```
            pecan
1b4_3b4
4b4_6b4     4
;
*_______________________________________________________________________
PARAMETER
crop_cycle(c) length of crop cycle - years
/
pecan           15
lucerne          6
maize            1
g_nuts           1
wheat            1
/
;
*_______________________________________________________________________
PARAMETER
irri_cycle(irri) economic life of irrigation system - years
/flood          1
pivot           15/
;
*_______________________________________________________________________
TABLE
grow(wt,c) growing season of crops
            pecan   lucerne  maize  g_nuts     wheat
wt1           1        1       1      1
wt2           1        1       1      1
wt3           1        1       1      1
wt4           1        1       1      1
wt5           1        1       1      1
wt6           1        1       1      1
wt7           1        1       1      1
wt8           1        1       1      1
wt9           1        1       1      1
wt10          1        1       1      1
wt11          1        1       1      1
wt12          1        1       1      1
wt13          1        1       1      1
wt14          1        1
wt15          1        1
wt16          1        1
wt17          1        1
wt18          1        1
wt19          1        1
wt20          1        1
wt21          1        1
wt22          1        1
wt23          1        1
wt24          1        1                           1
```

```
wt25            1     1                       1
wt26            1     1                       1
wt27            1     1                       1
wt28            1     1                       1
wt29            1     1                       1
wt30            1     1                       1
wt31            1     1                       1
wt32            1     1                       1
wt33            1     1                       1
wt34            1     1                       1
wt35            1     1                       1
wt36            1     1                       1
wt37            1     1                       1
wt38            1     1                       1
wt39            1     1           1           1
wt40            1     1           1           1
wt41            1     1           1           1
wt42            1     1           1           1
wt43            1     1           1           1
wt44            1     1           1
wt45            1     1     1     1
wt46            1     1     1     1
wt47            1     1     1     1
wt48            1     1     1     1
wt49            1     1     1     1
wt50            1     1     1     1
wt51            1     1     1     1
wt52            1     1     1     1
;
*____________________________________________________________________________
TABLE
gir(pg,irri,wt,m,c,pt)
$include "ImportGIR.gms"
*data is included from nother file due
*____________________________________________________________________________
TABLE
res_use(r,pg,p,wt,m,c,pt)  resource use by the crops - units per ha
                                    maize.yl
labour.1b4_3b4.flood.wt1.m1            0.01
;
*____________________________________________________________________________
TABLE
resource_f(f,wt,r) farm level resource availability - units per farm
              labour    tractor
farm32.wt1    99999      99999
;
*Labour and tractor hours at large levels - not consraining the solution
*____________________________________________________________________________
PARAMETER
```

```
alloc(f,t) volumetric water allocation to each farm - m3 per annum
;
parameter allocl(pg)

/
1b4_3b4       685500
4b4_6b4       685500
/
;
parameter allocl(pg);
alloc(f,t)=sum(pg,allocl(pg)*pg_to_f(pg,f));
;
display alloc;
*==========================================================================
*DATA INPUT: Resource availability and use
*==========================================================================
TABLE
irri_cost(ws,p) irrigation cost from water source to irrigation system - rand
per m3
                   flood    pivot
5c1_5c3_off        0        0.202
5c4_5c6_off        0        0.202
4b4_6b4_dam        0        0.182
;
*__________________________________________________________________________
PARAMETER
pump_cost(ws,dam) pumping cost from water source to dam - rand per m3
;
pump_cost(ws,dam)=0;
;
*__________________________________________________________________________
PARAMETER
tarrif(ws) primarary water abstracting tarrif - rand per m3
/
5c1_5c3_off   0.082
5c4_5c6_off   0.082
/
;
*__________________________________________________________________________
TABLE
invest_cap(pg,irri) investment capital to expand irrigation - rand per ha
           flood    pivot
1b4_3b4             10661
4b4_6b4             10661
;
*__________________________________________________________________________
PARAMETER
salvage_perc(irri) percentage salvage at end of economic life - %
/flood         0
```

```
 pivot          10/
;
*______________________________________________________________________________
TABLE
prices(f,c) average product prices - rand per unit
                 pecan   lucerne  maize  q_nuts     wheat
farm27           13500       900    900    3146      1200
farm32           13500       900    900    3146      1200
;
*______________________________________________________________________________
*BG
PARAMETER crop_yield(pg,p,m,c,t) average crop yields - units per ha;
$include "cropyields.prn"
;
* calculated in Excel
*______________________________________________________________________________
PARAMETER
operating_cap(pg,p,m,c,pt) operating capital - rand per ha;
$include "operating.prn"
;
* calcuated in Excel
*______________________________________________________________________________
TABLE
overheads(f,t) overhead expences
           y1          y2          y3*y15

farm27     263545      263545      215290
farm32     263545      263545      215290
;
*______________________________________________________________________________

TABLE
living_cost(f,t) household expences
           y1*y15
farm27     61239
farm32     61239
;
*______________________________________________________________________________

TABLE
max_operating(f,t) operating capital borrowing limit
           y1*y15
farm27     175000
farm32     175000
;
*______________________________________________________________________________

TABLE
max_borrow(f,t) investment capital borrowing limit
```

```
          y1*y15
farm27    175000
farm32    175000
;
*______________________________________________________________________

TABLE
borrow_threshold(f,t)  amount that can be borrowed each year
          y1*y15
farm27    175000
farm32    175000
;
*______________________________________________________________________

TABLE
reali(f,l) interest rates - %
                        borrow_ope borrow_inv      invest_bank
farm27                  10         17                5
farm32                  10         17                5
;
*______________________________________________________________________

TABLE
cap_aval(f,t) capital availability - rand
          y1
farm27    150000
farm32    150000
;
*______________________________________________________________________
SCALARS
df  discount factor - fraction /0.07/
tax_rate marginal tax rate -fraction /0.35/
;
```

APPENDIX **E**

PRODUCTION FUNCTION ENVELOPE

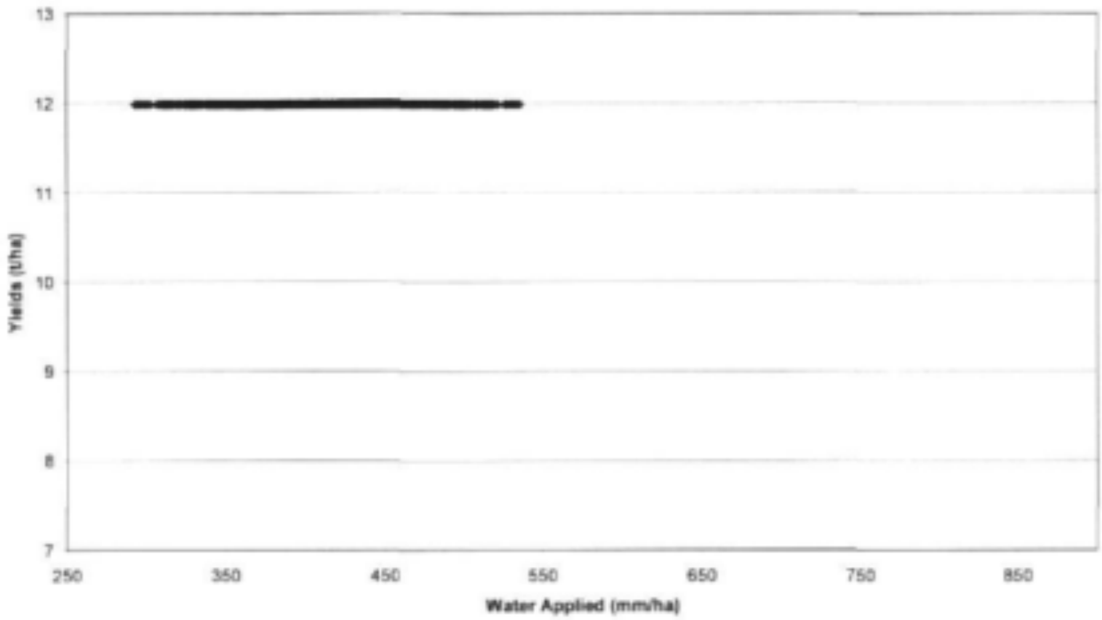

Figure E1: Envelope of technical efficiency on maize yields for different irrigation strategies during a favourable weather season.

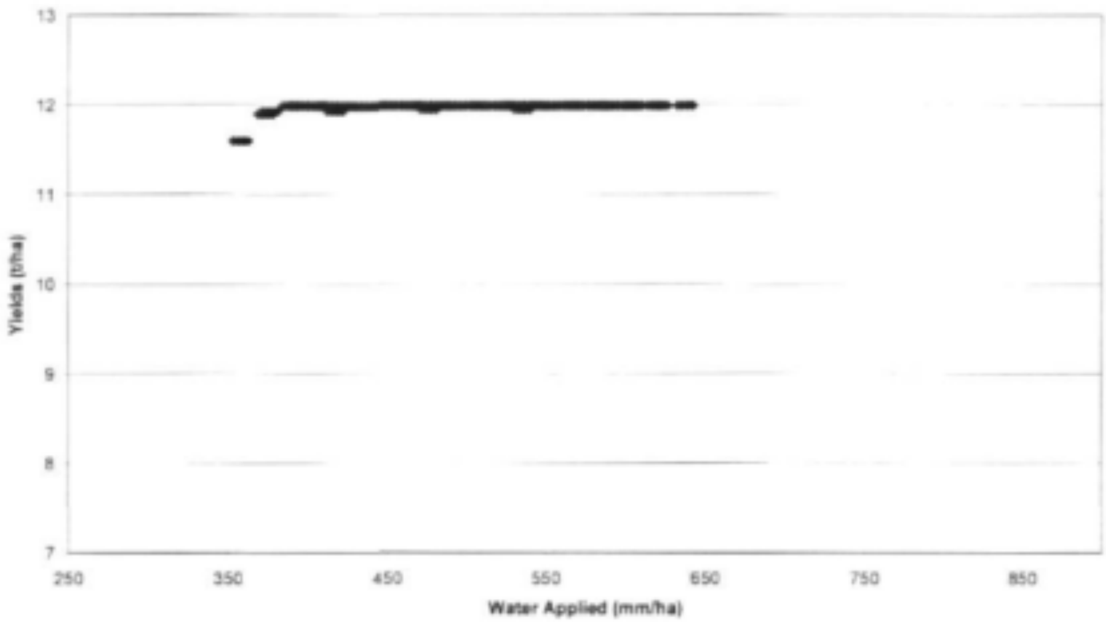

Figure E2: Envelope of technical efficiency on maize yields for different irrigation strategies during a normal weather season.

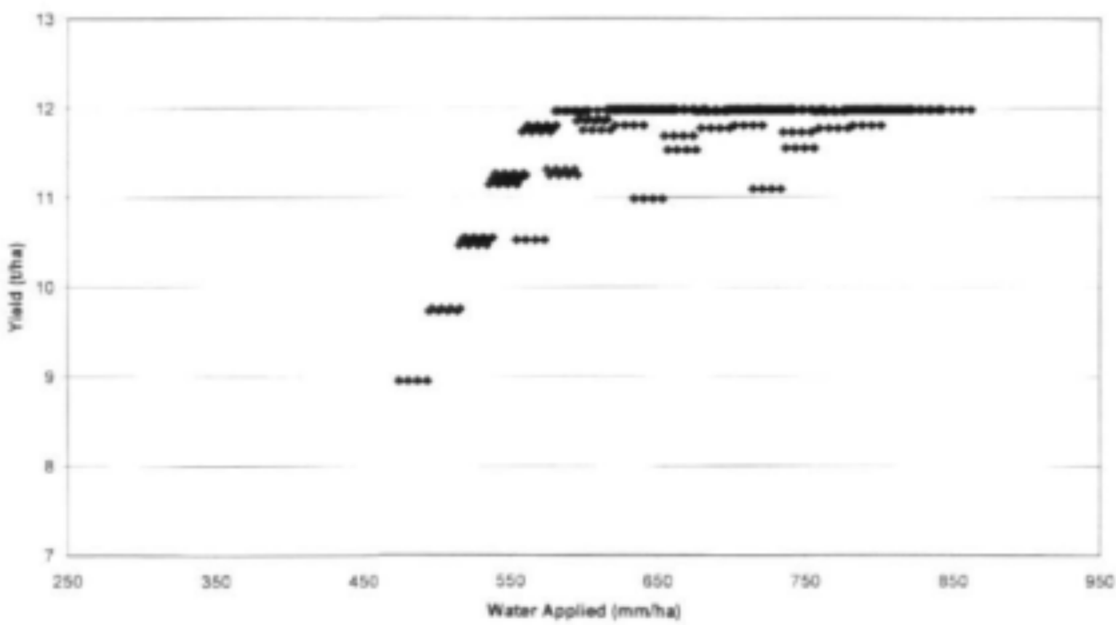

Figure E3: Envelope of technical efficiency on maize yields for different irrigation strategies during a severe weather season.

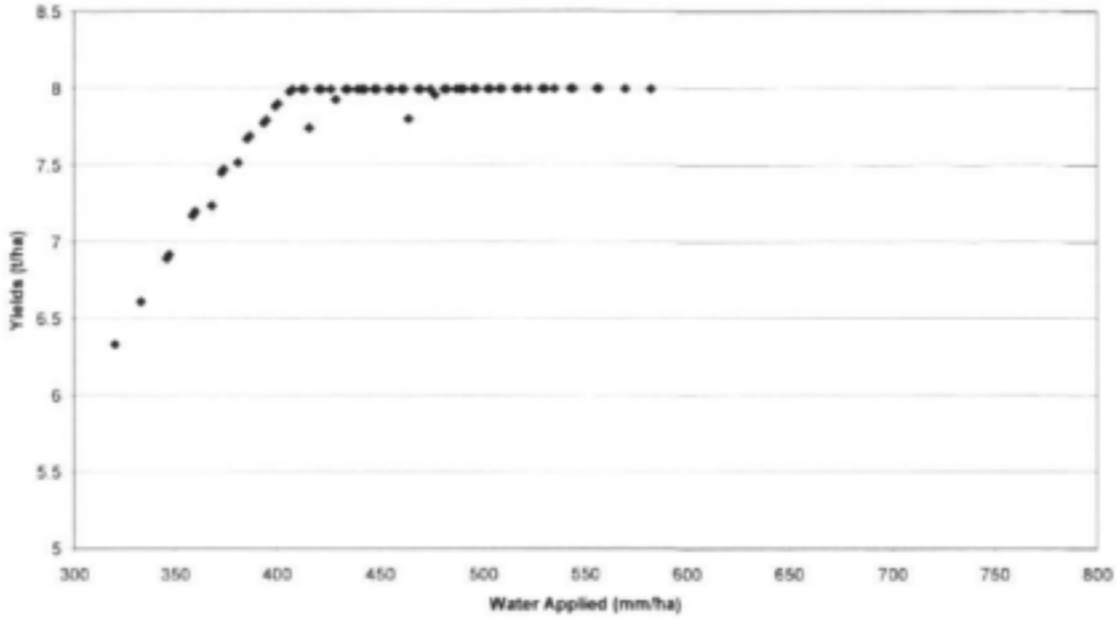

Figure E4: Envelope of technical efficiency on wheat yields for different irrigation strategies during a favourable weather season.

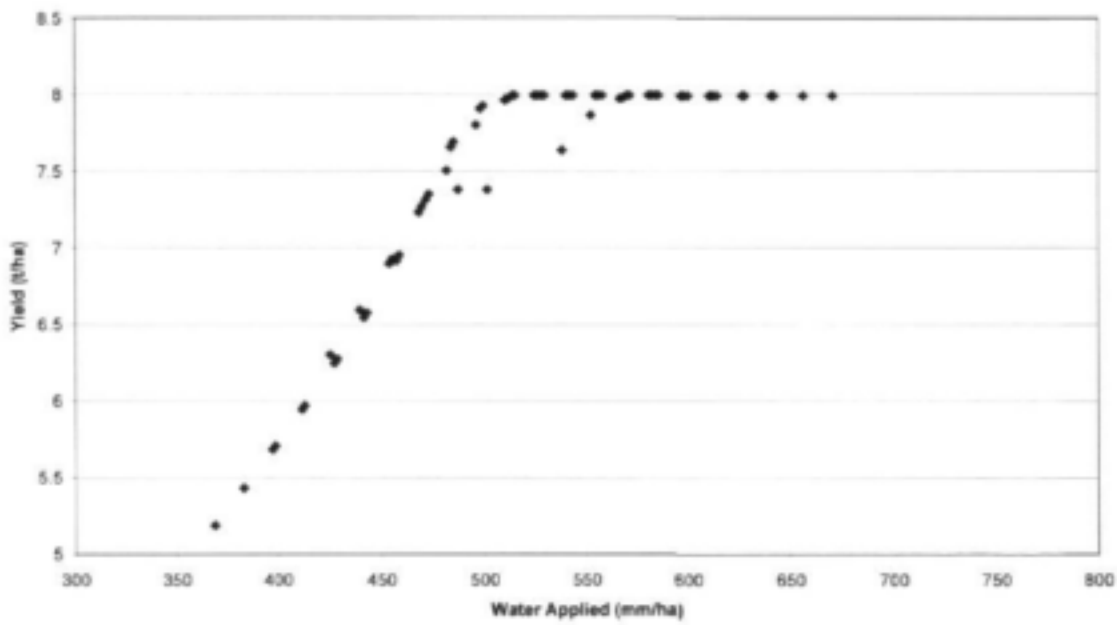

Figure E5: Envelope of technical efficiency on wheat yields for different irrigation strategies during a normal weather season.

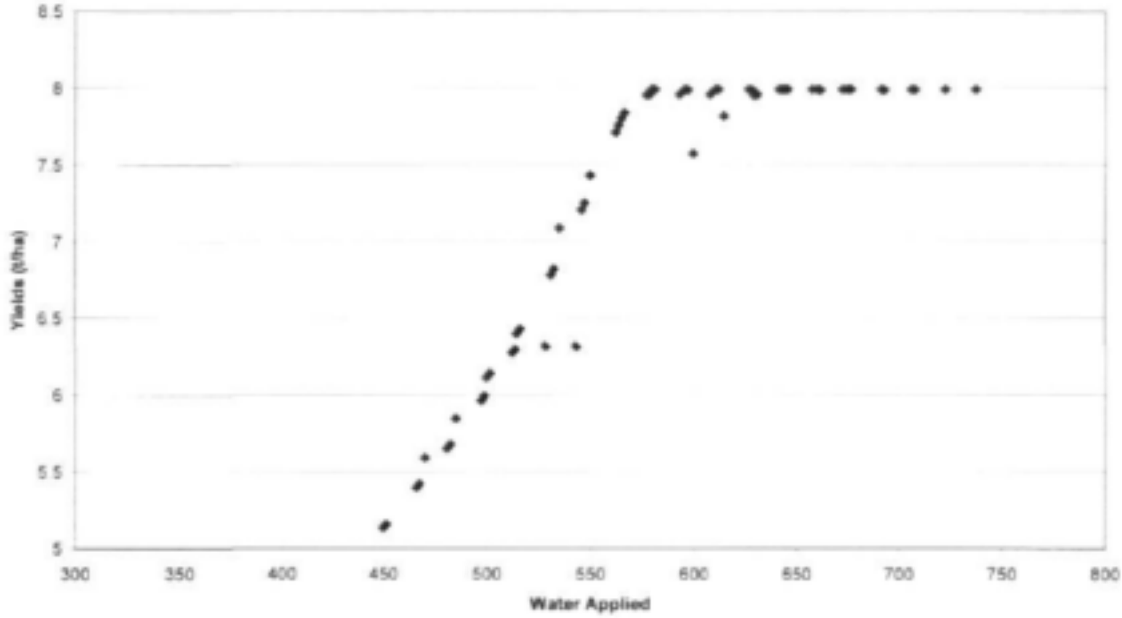

Figure E6: Envelope of technical efficiency on wheat yields for different irrigation strategies during a severe weather season.

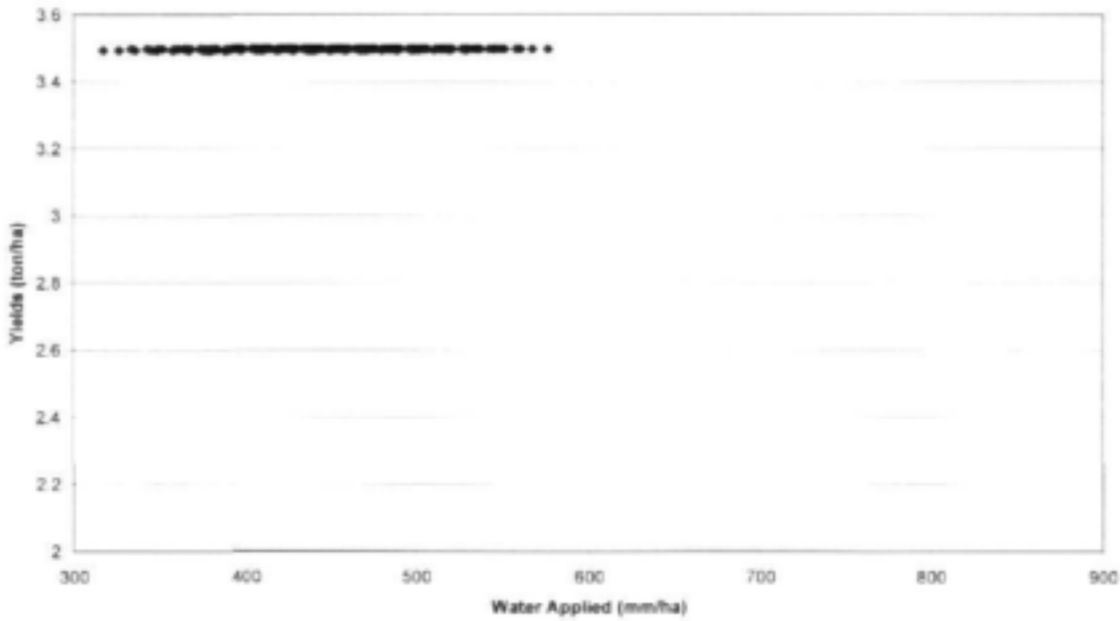

Figure E7: Envelope of technical efficiency on groundnut yields for different irrigation strategies during a favourable weather season.

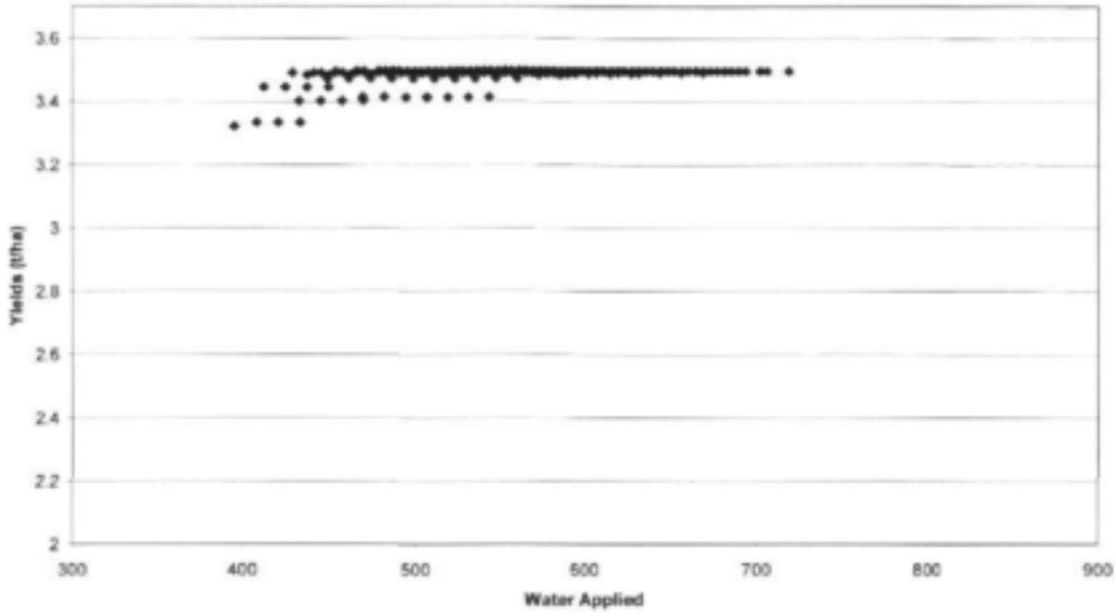

Figure E8: Envelope of technical efficiency on groundnut yields for different irrigation strategies during a normal weather season.

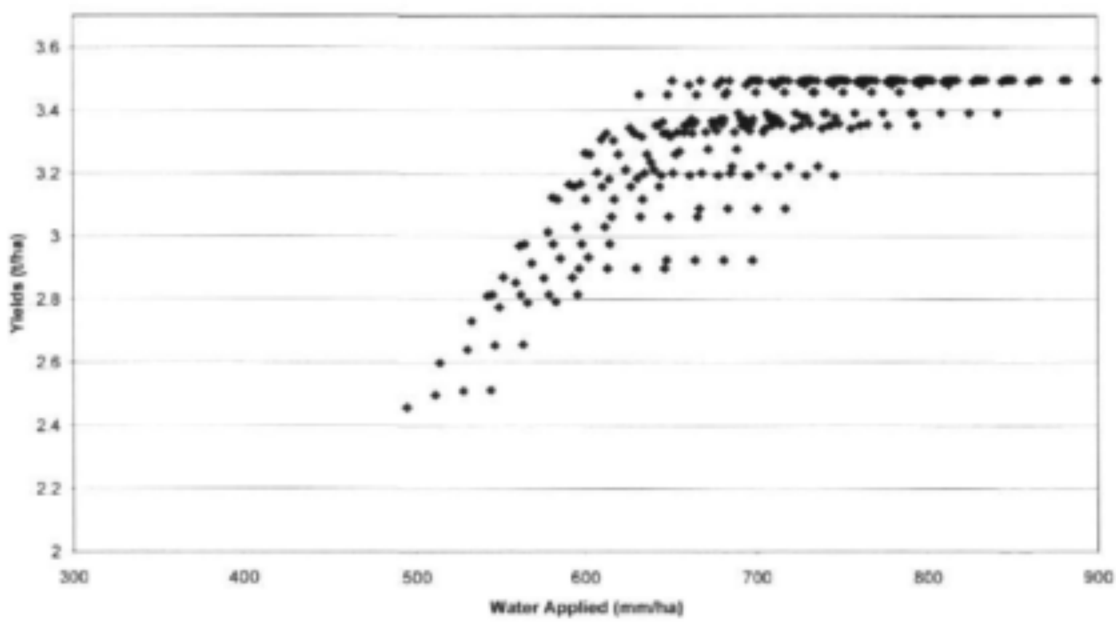

Figure E9: Envelope of technical efficiency on groundnut yields for different irrigation strategies during a severe weather season.

Other related WRC reports available:

Cost estimating procedures for micro-, drip- and furrow-irrigation systems as well as economic analyses of the relevant irrigation systems for large- and small-scale farmers in the Onderberg/Nkomazi region.

Oosthuizen LK; Botha PW; Grove B; Meiring JA; Pretorius IG; Monkhey MM

Irrigation farmers need to consider many technical, financial and economic factors when choosing or evaluating different irrigation systems. This research project proposes methods to estimate costs for various combinations of irrigation systems in the Onderberg and Nkomazi areas of the Mpumalanga Province. The research further demonstrates methods to analyse the profitability and financial feasibility of the various irrigation systems on a whole farming level.

The output of the research is, firstly, the cost estimating procedures which were developed for drip-, micro- and furrow-irrigation systems; secondly, that the cost of any combintion of the abovementioned irrigation systems together with centre pivot- and dragline-irrigation systems can be analysed; thirdly, that the economic analyses were done on a whole farm level, taking risk into account, for small-scale farmers on irrigation schemes, independent small-scale farmers as well as large-scale farmers. The general result was that cash flow is the biggest problem for all the farmers to different degrees. For the small-scale farmers the challenge is to survive financially and for large-scale farmers is to finance expensive irrigation systems and long-term crops such as orchards.

The cost estimating procedures should be used to estimate the total fixed and operating costs of the major irrigation systems. These procedures are suitable for on-farm use by irrigators and advisors. They can be used to decide over the long run which irrigation systems to buy, and in the short run how to manage the operating costs which are directly linked to the decisions of how much, how and what to produce.

Report Number: 974/1/05 **ISBN No: 1 77005 340 9**

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