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A STOCHASTIC ANALYSIS OF ON-FARM IRRIGATION DRAINAGE RECIRCULATION

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ABSTRACT

A number of environmental problems are associated with poor irrigation management. These include the economic costs of land salinisation and waterlogging, as a result of rising watertables, and the downstream impacts from irrigation drainage such as increasing river salinisation, turbidity and nutrient levels. Traditionally, engineering approaches have been used to address some of these problems, for instance the construction of regional surface drainage infrastructure to minimise the impact on agriculture from excessive irrigation runoff. The external costs associated with these options have generally been neglected. Moreover, they represent an attempt to address the symptom rather than the cause of the environmental problem.

Modification of on-farm irrigation behaviour, particularly with regard to the management of watertable leaching and irrigation runoff, represents an opportunity for minimising negative impacts upon the environment from irrigated agriculture. One such management option is the installation of an on-farm storage and drainage recirculation system so as to minimise, if not eliminate, irrigation runoff leaving the property. The success in achieving regional acceptance of such an option may require modification of existing policies, such as water pricing, the provision of district drainage infrastructure, the level of water supply security and pollution taxes.

The objective of this paper is to assess the benefits from the adoption of an on-farm irrigation drainage recirculation and/or storage system. From the farm perspective, the impact on net incomes, water management and agricultural enterprises are measured.

The system being evaluated is stochastic given that one of the benefits of a water storage system is the risk management involved with uncertain water supplies, either from rainfall or traditional allocation and off-allocation sources. The study has developed a stochastic framework whereby a multi-period linear programming model is solved iteratively with a number of stochastic right-hand side constraints. The analysis is then able to rank the alternative options on the basis of their stochastic dominance.

1. Introduction

1.1 Background

Environmental problems such as rising watertables, declining river quality and conflicts in the use of resources between agriculture and the environment within the Murray-Darling Basin have been widely documented (Grieve et al. 1986; Gutteridge, Haskins and Davey 1985; Jones and Marshall 1992; Quiggin 1988; Thomas and Jakeman 1985). Problems associated with rising watertables include reduced agricultural productivity due to soil and water salinisation and exacerbation of waterlogging. Declining water quality in river systems due to increasing salt, nutrient and chemical residue loads, turbidity and microbial activity has received increasing public attention. The regulation of flow in river systems and consequent impacts on riparian habitats is also receiving increasing attention, raising questions regarding the efficiency of water allocation between agricultural and environmental uses. A range of policies have been developed to address these problems, including the Salinity and Drainage, Natural Resource Management and Irrigation Management Strategies of the Murray-Darling Basin Commission (Murray-Darling Basin Commission Ministerial Council 1988, 1989), revision of water allocation and pricing policies as well as the application of the principles of integrated catchment management to problems of resource degradation.

A major contributor to rising watertables and declining river quality is the on-farm management of irrigation and drainage water. The *NSW Integrated Drainage Policy for Irrigated Areas* recognises that "the proper handling of physical and management factors on-farm is vital if the problems of reduced productivity and degradation of the environment caused by past practices and inadequate drainage are to be addressed" (Department of Water Resources, NSW Agriculture and Total Catchment Management 1992, p. 12).

Land and Water Management Plans (L&WMPs) for a number of irrigated regions in southern NSW are currently being developed under the *NSW Integrated Drainage Policy for Irrigated Areas*. Communities in irrigated areas assume responsibility for the formulation of L&WMPs, which aim to address problems of resource degradation through the development and implementation of medium term strategies that provide for the continued economic and environmental sustainability of these regions.

1.2 The Berriquin Irrigation District

The Berriquin Irrigation District (BID) is located in the Murray Valley of NSW between the towns of Berrigan and Deniliquin and covers an area of 321,000 hectares. Irrigation and drainage practices in the BID have contributed to the development of high watertables across a large proportion of the district. In 1990, 28.5 per cent of the BID had watertables within two metres of the surface[1] (P.H. Jacobs and Associates 1993). If current irrigation and drainage practices are continued, it is predicted that 62.5 per cent of the area will be affected by 2020.

Problems associated with high watertables include reduced agricultural productivity due to soil and water salinisation and exacerbation of waterlogging. The estimated current agricultural gross

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[1] Once a watertable rises to a critical depth from the soil surface, which is considered to be two metres in the Murray-Darling Basin, upward movement of salt into the root zone can occur due to capillary rise of saline moisture from the watertable. Capillary rise involves the upward movement of water and dissolved salts through the soil profile due to evaporation at the soil surface

margin foregone due to soil salinity of $1.2 million per year is predicted to increase to $3.1 million by 2020 (P.H. Jacobs and Associates 1993). It is likely that further losses would occur from exacerbation of waterlogging.

A L&WMP is currently being developed for the BID, which addresses a range of areas of concern including off-farm surface drainage works, sub-surface drainage works, infrastructure refurbishment, institutional change and on-farm irrigation management.

The study reported here is one component of a wider economic analysis of on-farm options to assist the development of a cost effective L&WMP. The aims of the on-farm component of the Berriquin L&WMP are: first, to improve irrigation management and farm productivity; second to reduce the amount of water entering the watertable on-farm; and third, to manage saline areas and areas of high watertables (Berriquin Land and Water Management Plan 1993).

Drainage recirculation and on-farm storage systems are among the on-farm measures with potential to improve drainage management, thereby increasing farm productivity and reducing watertable accessions.

1.3 Drainage recirculation, water harvesting and on-farm storage

Drainage recirculation involves the drainage of surplus irrigation water to a storage for later reuse while water harvesting entails the collection and storage of storm runoff. The benefits from a recirculation system involves the reduction in groundwater accessions and waterlogging, increased water supply, and having irrigation water on demand rather than being constrained by the capacity of the irrigation supply system.

The benefits of reducing the frequency and duration of waterlogging events are from removing ponded surface drainage from low-lying points of a farm. This is particularly beneficial where there is no access from these low-lying points into an off-farm drainage line. Due to the reduction in surface ponding water entering the watertable is reduced, as are crop, pasture and livestock management problems associated with waterlogging.

Where drainage into off-farm lines is possible, reduced disposal of water into these lines as a result of recirculation can have downstream consequences by affecting total volumes of water discharged downstream and overall concentrations of salt, nutrients and biocides in that water.

Water obtained from drainage recirculation may be used to substitute for, or supplement, water available through the district supply network. This can be beneficial because supply through the district network is limited in volume by irrigation allocation and availability of off-allocation flows and in delivery rate by the capacities of district supply channels. Evaluation of drainage recirculation as a means of water supply supplementation, however, requires comparison with alternative opportunities for supplementation. These include pumping of good quality groundwater or purchase of additional water entitlement.

The benefits obtained from drainage recirculation and water harvesting will, however, be constrained by, (a) the extent to which the engineering capacity of the drainage recirculation system is adequate to manage actual drainage volumes, and (b) the scope to use, or dispose of, runoff at any time is limited by irrigation requirements at that time and by airspace within on-farm channels, drains and storages.

Installation of an on-farm water storage offers benefits in terms of increasing the capacity of a drainage recirculation system to cope with waterlogging events, resulting in reduced watertable accessions and surface drainage volumes. A storage also provides increased scope for harvesting water from sources other than irrigation runoff such as rainfall runoff, spearpoints, off-allocation flows and transferring unused allocation volumes to the next season by putting it into storage. By increasing the capacity of a farmer to utilise drainage, off-allocation supplies and groundwater, a storage can also reduce the need to purchase water, increase water availability, or both. Investment in on-farm storage can also provide significant benefits through increased irrigation management flexibility, by allowing irrigation to commence before water is available in the supply system.

1.4 Uncertainty of water supply

Recirculation and on-farm storage systems have the potential to increase farm incomes by reducing production losses due to waterlogging, as well as allowing more intensive irrigation by augmenting the farm water supply. In addition, the variability of farm incomes may be reduced by affording farmers opportunities for tactical response to unforeseen water supply outcomes (e.g., with respect to allocation percentage, off-allocation flow volume and rainfall).

A drainage recirculation and storage system may allow additional water for irrigation to be obtained during periods of low irrigation allocation by reuse of irrigation drainage and harvesting of off-allocation flows and rainfall runoff. Alternatively, during periods of high rainfall, ponding of runoff on low-lying areas of the farm can be minimised through recirculation and storage, thereby reducing production losses due to waterlogging.

The financial benefits obtained from investment in a drainage recirculation and storage system will be influenced by the volumes of irrigation drainage reused and volumes of off-allocation flow and rainfall runoff harvested, as well as the availability of irrigation water through the district supply system. As these water supply variables are stochastic in nature, it is important to account for the range of possible water supply outcomes when undertaking a financial analysis of investment in drainage recirculation and on-farm storage systems.

1.5 Objectives of the study

The primary objective of this study was to undertake a financial analysis of the benefits of a range of alternative drainage recirculation and on-farm storage systems for a representative farm in Berriquin Irrigation District. A further objective was to determine whether the externalities associated with the management of irrigation and drainage water are reduced by the adoption of a drainage recirculation and storage system.

The benefits are determined by comparing the returns for each alternative with a base "do nothing" scenario. The impact of uncertainty in allocation supplies, off-allocation flows and rainfall is taken into account by the use of a stochastic programming approach with stochastic dominance procedures used to assess and rank the risk efficiency of the alternatives.

1.6 Outline of the paper

The nature of risk, alternative stochastic methodologies and the principles of stochastic dominance are discussed in Section 2. Information concerning the specification of the simulation, linear programming and benefit-cost models developed is presented in Section 3. In Section 4 results are presented, and a summary and discussion of results presented in Section 5.

2. Review of Risk in Farm Planning

2.1 Nature of risk

For many problems involving uncertainty a stochastic analysis is able to account for the outliers from probability distributions of random variables which cannot be reflected in the expected values of a deterministic study. The stochastic approach is, therefore, more able to accurately measure the benefits and costs associated with a decision problem.

A wide variety of approaches have been developed to deal with risk in farm decision making. These range from optimising procedures, based on linear, non-linear and dynamic programming, to non-optimising (such as stochastic budgeting and risk efficient monte-carlo programming). It is important to understand the exact nature of risk that is involved in the problem under review so as to identify the most appropriate methodology for undertaking the analysis.

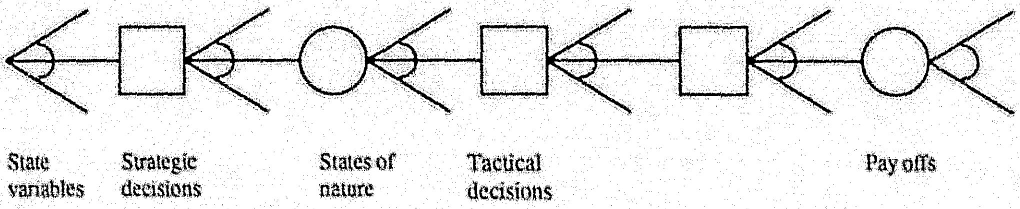
Hardaker, Pandey and Patten (1991) distinguish between two types of risk; non-embedded and embedded. In the non-embedded case the assumption is that it is realistic to model the system as if all decisions are made initially and then the uncertainty unfolds subsequently in terms of risky consequences of the choice taken. In the case of embedded risk, the decisions are segregated into those taken initially and those taken at a later stage when some uncertainty has unfolded. The second stage decisions will be conditioned by both the initial choices and the revealed uncertain outcomes. Most farm decision problems involve embedded risk, however, many mathematical programming approaches which incorporate uncertainty do not account for embedded risk. Generally, non-embedded risk is confined to objective function coefficients while for embedded risk both the objective function and constraint coefficients can be stochastic. Hardaker et al classify models which account for risk in the objective function as risk programming models while models which incorporate risk in the input-output coefficients or level of constraint variables can be termed as stochastic programming models.

Embedded risk was considered critical to the evaluation of the problem under review with the main sources of uncertainty identified as being allocation supplies, off-allocation flows and rainfall. The study was, therefore, more concerned with the range of possible stochastic programming approaches, which treat situations of embedded risk, rather than with risk programming approaches.

When embedded risk is a feature of the decision problem under review the researcher must be aware of the type of responses to risk an individual decision maker can take. These possible responses are categorised as either strategic or tactical (Trebeck and Hardaker 1972; Kingwell, Pannell and Robinson 1993). A farmer's decision making is generally sequential in nature; as a season (or other decision period) unfolds a farmer will make tactical decisions in response to the intervening states of nature and the initial strategic decisions made (Figure 1). Trebeck and Hardaker demonstrated the use of this sequential approach to identify optimal beef cattle carrying capacity strategic decisions and tactical decisions related to cattle management throughout a number of seasons subject to uncertain rainfall over the pasture growing season.

The purpose of solving the sequential decision problem is to evaluate the performance of the initial strategic decision(s). Neglecting the role of tactical adjustments in the process can lead to an underestimation of the profitability of some strategies (Kingwell et al).

Figure 1: Sequential decision making



Source: Trebeck and Hardaker 1972.

Identification of the components of the sequential decision making process associated with this study are outlined below. This assists the assessment of the alternative stochastic methodologies possible for this analysis.

State variables
Farm size, soil type, licensed allocation, irrigation layout, labour availability, machinery availability, commodity prices, farmer skills
Strategic decisions
Size of recirculation system (if any), size of on-farm storage system (if any), initial livestock carrying capacity, rotation type, district surface drainage.
States of nature
Allocation supplies, off-allocation flows, rainfall.
Tactical decisions
Adjust crop and pasture areas, make fodder, buy fodder, sell fodder, buy livestock, sell livestock, buy transferable water entitlements (TWE), sell TWE, recirculate irrigation runoff, dispose irrigation runoff to district drainage, capture and recirculate rainfall runoff for irrigation, dispose rainfall runoff to district drainage, allow irrigation and rainfall runoff to pond and recharge watertable, store recirculated water for use in later periods (months), use off-allocation in current period, store off-allocation.
Pay offs
Whole farm gross margin, net present value.

2.2 Alternative stochastic methodologies

As identified in the previous section the treatment of risk in programming models differs according to whether non-embedded or embedded risk is present. Risk programming approaches which have gained wide acceptance are quadratic risk programming (Freund 1956), minimisation of total absolute deviations, or MOTAD (Hazell 1971), Target MOTAD (Hauer 1983), mean-Gini programming (Yitzhaki 1982), utility maximisation (Lambert and McCarl 1985) and utility-efficient programming (Patten, Hardaker and Pannell 1988). The major stochastic programming approaches usually considered are chance-constrained programming, risk efficient monte-carlo programming and discrete stochastic programming (DSP). Stochastic dynamic programming can also be used for problems which are sequential in nature. As embedded risk is the main feature of the drainage recirculation problem, further discussion is confined to the alternative stochastic programming methodologies.

Early efforts to introduce random variables into the input-output coefficients and right-hand side vectors were presented by Tintner (1955) and Johnson, Tefertiller and Moore (1967)[2]. The approach used by Tintner was to incorporate cumulative probability functions for the random variables in the objective function, input-output and right-hand side variables in a linear programming model. Rae (1971b) termed this approach a passive stochastic programming formulation, the model requiring perfect knowledge of the random events.

Johnson et al used a similar approach to Tintner. A stochastic linear programming model of the following form was developed:

$$\max z = \sum_{j=1}^{n} c_j x_j$$

$$st \quad \sum_{j=1}^{n} a_{ij} x_j \leq b_i$$

In the linear programming model at least one of the elements c_j, a_{ij} and b_i is a random variable. If the random variable is observed before the selection of the decision vector, then the resulting problem to be solved is a deterministic linear programming problem. The model becomes:

$$f(c_j, a_{ij}, b_i) = \sum_{j=1}^{n} c_j x_j$$

$$st \quad \sum_{j=1}^{n} a_{ij} x_j \leq b_i$$

Since at least one of the elements of c_j, a_{ij} or b_i is a random variable with a specified distribution function, $f(c_j, a_{ij}, b_i)$ will also have an associated distribution function. A set of variates drawn from probability distributions for the random elements in c_j, a_{ij} and b_i is substituted for stochastic parameters in the problem. Letting the nonstochastic components be ς_j, $\tilde{a}_{ij}$ and β_i then the value of the criterion function in the solution to the associated deterministic linear programming problem $f(\varsigma_j, \tilde{a}_{ij}, \beta_i)$ is a variate from the probability function $f(c_j, a_{ij}, b_i)$. By repeating the procedure the distribution function for $f(c_j, a_{ij}, b_i)$ can be approximated. Johnson et al define this procedure of finding the distribution function the 'distribution problem'. A number of solutions of the linear programming problem are required to approximate the distribution function, the number depending upon the precision with which $f(c_j, a_{ij}, b_i)$ is to be approximated. In their study Johnson et al undertook only 20 sets of random samples and solutions. A more comprehensive sampling process using far greater than the 20 samples was, possibly, too expensive due to the constraints upon computing resources at that time.

Rae (1970) noted a possible problem with the Johnson et al approach when applied to a capital budgeting problem. As the activity levels may vary from one solution to another, there will be a probability distribution with, for example, investment activities as well as net income. Given the existence of these distributions it may be difficult to determine the optimal program for a decision maker to adopt.

Chance-constrained programming, where risk is dealt with indirectly by setting a probability with which the constraints must be satisfied, has been strongly criticised (Anderson, Dillon and Hardaker 1977; Hardaker, Pandey and Patten 1991) on the basis that it becomes impractical if

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[2] Other presentations can be found in Radner (1959), Merrill (1967) and Evers (1967).

several stochastic constraints are to be accommodated, it suffers from an arbitrary choice of probability levels and the critical level of probability is itself a part of the decision problem. Consequently chance-constrained programming is considered no further in this analysis.

Risk efficient monte-carlo programming has been advanced by Anderson (1975) as a realistic alternative to mathematical programming in accounting for risk. In this approach the planning problem is set out in a similar fashion to that of programming methods but portfolios of activity levels are selected at random. These portfolios are first tested for feasibility and then evaluated in terms of some specific objective function. The procedure is one of search with a large number of portfolios being sampled.

This approach can easily incorporate stochastic elements in the objective function and constraint equations. The results of this type of analysis are generally tested for stochastic dominance which serves to sort feasible plans into efficient plans and inefficient plans.

The advantage of risk efficient monte-carlo programming is that it is extremely amenable to the incorporation of continuous probability functions for random variables, rather than being limited to a finite number of discrete variables. Moreover, any objective function can be applied (linear or non-linear), and utility functions can be defined. This approach is particularly useful for problems when risk is non-normal and when the extent of farmers' risk aversion is unknown.

DSP was first formulated by Cocks (1968) and advanced by Rae (1971a,b) as a means of linear programming to analyse multistage stochastic problems in which the optimal activity in one period depends on events in past periods. This method has emerged as a popular approach for accounting for embedded risk in an optimising framework.

DSP offers a framework where any or all of the c_j, a_{ij} and b_i elements of a mathematical programming model can be random. Discrete parameter values or states of nature are used to represent the range of possible coefficient values. DSP also captures the flow of information to the decision maker about the values of objective function and constraint set parameters and matches that flow of information to the sequences of decisions to be made (Apland and Hauer 1993). This is done through the specification of decision stages in which decisions are made.

Problems of dimensionality and large matrix size were noted in early applications of DSP (Cocks 1968; Rae 1971b; Trebeck and Hardaker 1972). According to Apland and Hauer (1993, p.28) these technical problems appear to have been overcome as "the range of model sizes suggests that for many applications of DSP, analysts have found the desired level of model performance well within the capabilities of current mathematical software". Despite these developments, the problems associated with verifying and validating large models, which invariably accompany DSP, remain a deterrent to its use (Hardaker, Pandey and Patten 1991).

Dynamic programming is a technique which is well suited to intertemporal optimisation problems and can take account of stochastic elements. Dynamic programming is often a useful technique for evaluating the optimal management of natural resources with a number of applications being applied to irrigated agriculture (Yaron and Bresler 1970; Yaron and Olian 1973; Bras and Cordova 1981; Yakowitz 1982; Dinar and Knapp 1986). The principles of dynamic programming are well described elsewhere (for example Burt and Allison 1963; Throsby 1964; Burt 1969, 1982; Dorfman 1969; Kennedy 1981, 1986) and so are not dealt with in this paper.

2.3 Stochastic methodology adopted

The major limitation in applying risk efficient monte-carlo programming is the lack of optimising features. In farming situations where resource usage decision choices are limited, for instance mono-culture and permanent plantings, there is little problem with using a simulation approach. In farming systems where there is considerable scope for alternative activities mathematical programming approaches have a distinct advantage when searching for optimal resource use management and policies. The latter is the case for Berriquin Irrigation District. The optimal management of water resources, both supply and drainage, in each of the decision stages that can be given by an optimising approach is particularly valuable for this study. The use of risk efficient monte-carlo programming was rejected for this reason.

The use of stochastic dynamic programming was not considered necessary for the study of drainage recirculation for two reasons. First, dimensionality problems associated with a stochastic dynamic programming formulation of the problem under review would become substantial if all the complex interactions between environmental, physical and economic systems were to be represented. This, however, could have been overcome by developing a linear programming model to account for all these relationships and to provide the stage returns for each stage of the dynamic programming problem (for example total farm gross margin for each level of water allocation). Such an approach would add to the research cost involved with this study.

More importantly, the nature of irrigation water supply systems in southern NSW is such that uncertainty only involves water availability between years and not within years. The region is typified by predominately winter rainfall, with very dry summers meaning that rainfall contributes very little to the summer water requirements of plants, and the total summer evapotranspiration does not vary much from year to year. Water supply available for the irrigation season is generally known with a degree of certainty prior to the commencement of the irrigation season, with uncertainty essentially limited to irrigation supply between irrigation seasons. Known supply and demand for the intermediate irrigation season permits the use of methods such as linear programming with a high degree of accuracy (Dudley 1990). If uncertainty existed in the supply and demand for water within the season then the sequential optimising process of dynamic programming may be preferred.

The manner in which embedded risk is accounted in a DSP framework, through the representation of strategic and tactical risk responses, has considerable appeal. However, several drawbacks were identified with applying DSP in this study.

The representation of a continuous probability distribution in DSP requires the specification of a number of discrete variables, the exact number depending upon the desired accuracy of the distribution. Depending upon the nature of the problem, dimensionality can become an issue. Rae (1971b, p.635) notes "an increase in the number of random variables, the number of possible values of each random variable, or the number of decision dates within the planning period will result in a more than proportionate increase in the size of the programming matrix. Thus a dimensionality problem exists and, with limited research funds, it is important that the model be *economically justified*[3] ".

The ideal approach when developing a DSP model would be to specify as many discrete variables as possible to perfectly represent a continuous probability function for a random variable. For example, 140 discrete variables could be used to represent the possible values annual water

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[3] Our emphasis.

allocation could take, i.e. 0 to the maximum of 140 per cent. A compromise between the desired level of accuracy and having a manageable model is required if dimensionality problems are to be kept to a minimum. Thus the number of discrete variables are usually kept to as few as practically possible.

With the dimensionality constraint in mind the recirculation and storage problem could have been specified with 8 discrete variables for allocation supplies, 2 for off-allocation supplies and 4 for rainfall runoff[4]. There are 12 time periods to be represented, resulting in 768 sub-matrices. Reducing the time periods from monthly to seasonal (spring, summer, autumn and winter) the minimum number of sub-matrices required for an adequate representation of the drainage recirculation problems becomes 256. The construction, verification and validation of what is still an extremely large model was not considered "economically justified" to use Rae's term.

The stochastic programming approach that was adopted to evaluate the drainage recirculation problem is an extension to that presented by Johnson et al and Tintner. There are a number of advantages of this distribution problem approach over DSP. First, it was possible to specify the random variables as having continuous probability distributions rather than having to take a pre-determined finite number of discrete variables to represent the distribution. Second, the model developed was significantly smaller, with 12 sub-matrices representing the time periods as opposed to a minimum of 256, much larger, sub-matrices associated with a DSP approach. Thus, there was a significant reduction in the costs involved with the development, verification and validation of the model. Third, the approach can more easily accommodate correlation between the random variables and autocorrelation within the random variables. Like DSP and risk efficient monte-carlo programming, the distribution problem approach can accommodate any distribution form for the random variables.

The approach presented by Johnson et al has been modified so as to meet the concerns expressed by Rae (1970) and to account more accurately for the embedded risk and possible tactical responses available to farmers. The outcome of this modification was that the investment activities remained fixed during the solution so no probability distributions were associated with these variables. Therefore, it was possible to choose an optimal strategy.

A simulation model was developed which controlled the execution of the stochastic programming process. The strategic actions available to individual farmers and the random states of nature were specified in the simulation model, while all possible tactical responses were represented in the linear programming model (Figure 2). The simulation model contained continuous probability distributions for each of the random variables as well as information relating to fixed variables required by the linear programming model.

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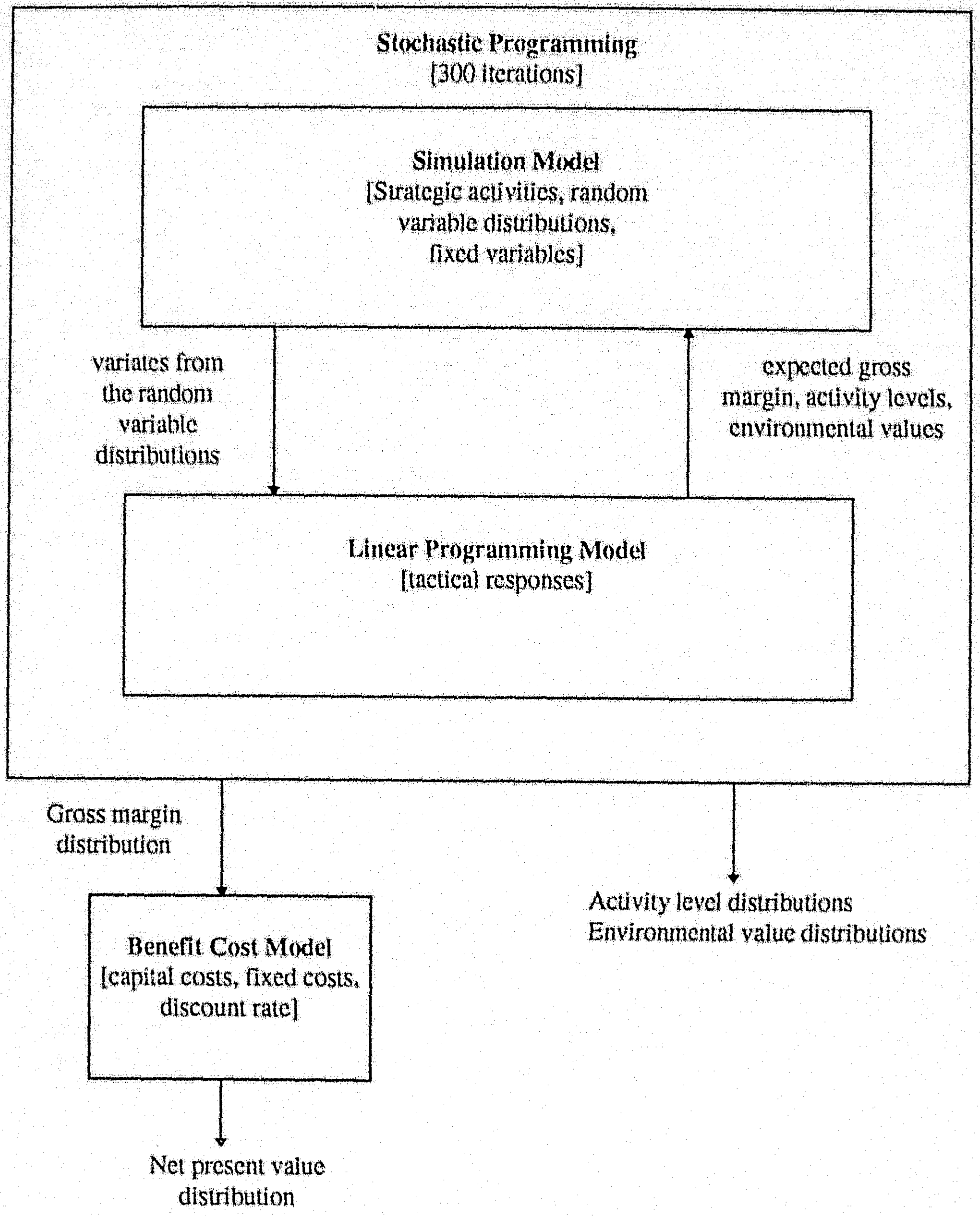
[4] The discrete variables were 0 to 140 per cent in 20 per cent increments for allocation supplies, 0 or 450 megalitres for off-allocation supplies, and "low", "medium", "high" and "very high" for rainfall runoff

Figure 2: Sequence of stochastic analysis



The process of analysis involved specifying within the simulation model a strategic decision as being constant for a complete simulation. Following the procedure of Johnson et al ,for each iteration of the simulation[5] the probability distributions of the random variables were sampled using a sampling procedure[6] with the resulting variates drawn from the distribution being substituted into the linear programming model. The linear programming model was solved in the standard deterministic fashion and provided the optimal tactical decisions in response to the values of the random variables drawn from the probability distributions for that iteration and the initial strategic decision. The process was repeated for each iteration. Results determined at the completion of this process included means, variances and higher moments as well as the distribution functions of the objective function and a number of selected output variables.

A feature of this approach wa[illegible] t was possible to make the values of some random variables in iteration *t* directly related to the values in iteration *t-1* due to autocorrelation (where a serial correlation coefficient is used to determine the values of, for example, water allocation) and due to recursive reasons (for example, sheep numbers at the beginning of iteration *t* must equal sheep numbers at the end of iteration *t-1*).

The ease of execution of this procedure has been greatly enhanced by the development of software programs such as @RISK™ (Palisade 1992) and spreadsheet based linear programs. In this study @RISK™ was used to specify the distributions of the random variables, conduct the random sampling, execute the simulation and report the results. A spreadsheet based linear program, What's Best!™ (Savage 1992), solved the model for each @RISK™ iteration. The entire procedure was driven by a spreadsheet macro program with no input required of the researcher other than specification of the initial strategic decision.

The 'distribution problem' as used in this study implies the random variables are observed prior to the period in which the tactical decisions are made. Such an approach is consistent with the nature of the climate and irrigation supply system in BID.

The use of linear programming for determining the tactical responses for each iteration implies risk-neutrality on the part of farmers. As there is considerable information at the commencement of the season regarding water availability for the forthcoming irrigation, risk-neutrality with regard to within season planning decisions based on water availability is defensible. The assumption of risk neutrality regarding non-embedded risk in the objective function values is less defensible. Methods such as MOTAD, or preferably the linear segmented utility-efficient programming approach presented by Patten, Hardaker and Pannell (1988), could be included in the model specification. Given that these methods are solved parametrically, this poses execution problems for the iterative nature of this stochastic programming approach. One option may be to initially solve a utility-efficient programming model of the problem and then use the choice of activities as strategic variables. A less rigorous approach may be to specify returns for the commodities as random variables. However, this approach also does not capture the tactical responses regarding non-embedded risk that may be made by a risk-averse decision maker. Clearly this is an area which requires greater attention in future research.

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[5] In this study 300 iterations were used to calculate the probability distributions. This is a marked improvement on the 20 iterations used by Johnson et al.

[6] Monte Carlo sampling is the traditional technique for using random or pseudo-random numbers to sample from a probability distribution. Latin Hypercube is an alternative sampling procedure which requires fewer iterations when compared to the Monte Carlo sampling approach. This is achieved through stratification of the input probability distributions. The latter sampling procedure was used in this study.

It is probable that the assumption of risk-neutrality in respect to the strategic options is more contentious than the tactical decisions considering the capital costs involved and the long time horizons which these investments can take. In the case of a drainage recirculation and on-farm storage system, this is a relevant issue as one of the possible benefits is the minimisation of variance in annual net returns between years. This study was conducted on the basis that farmers were risk-neutral for determining annual tactical responses and considers both risk-neutral and risk-averse assumptions in regard to the choice of alternative strategies.

2.4 Stochastic dominance

In many cases of agricultural research the preferences of individual farmers to risk may be unknown due to the difficulties and costs involved in eliciting such preferences. A procedure known as stochastic dominance (Anderson 1974; Anderson, Dillon and Hardaker 1977) can be used to identify and rank risk efficient strategies when preferences are unknown.

First-degree stochastic dominance (FSD) presumes that decision makers prefer more to less of a measure of consequence such as profit, x, implying that the function $U(x)$ is monotonically increasing i.e. the first derivative is positive, $U_1(x) > 0$. The distribution $f(x)$ dominates $g(x)$ by FSD if $F_1(R) \leq G_1(R)$ for all possible R with a strict inequality for at least one value of R.

Second-degree stochastic dominance (SSD) adds the assumption that the decision maker is risk averse. Thus, the function $U_1(x)$ is not only monotonically increasing but is concave i.e. the second derivative $U_2(x) < 0$. The distribution $f(x)$ dominates $g(x)$ by SSD if $F_2(R) \leq G_2(R)$ for all possible R with a strict inequality for at least one value of R.

The concept of third-degree stochastic dominance (TSD) rests on an additional assumption that the third derivative is positive, $U_3(x) > 0$. This restriction is implied by the requirement that decision makers become decreasingly averse to risk as they become more wealthy. The distribution $f(x)$ is thus said to dominate $g(x)$ by TSD if $F_3(R) \leq G_3(R)$ for all possible R with a strict inequality for at least one value of R and if $F_2(b) \leq G_2(b)$, where b is the upper range.

An extension to the concept of SSD is stochastic dominance with respect to a function (SDRF) developed by Meyer (1977a,b) which allows the ranking of risky strategies consistent with the maximisation of expected utility. SDRF requires the explicit definition of a class of admissible utility functions, the admissible class usually being called the preference interval and is specified in terms of bounds on Pratt's (1964) coefficient of absolute risk aversion, $r(x)$, defined as the negative ratio of the second and first derivatives of the utility of the wealth function $u(x)$

$$r(x) = -u''(x)/u'(x)$$

This approach estimates the necessary and sufficient conditions for the distribution of outcomes defined by the cumulative distribution function $f(x)$ to be preferred to that defined by the cumulative distribution function $g(x)$ by all individuals whose absolute risk aversion lie everywhere between lower and upper bounds $r_1(x)$ and $r_2(x)$. The power of the technique to discriminate between alternatives is related to the tightness of the bounds that can be placed on $r(x)$. A maximum range of 0.5 (risk-neutral) to 4 (extreme risk-aversion) for the coefficient of relative risk aversion, $r_R(x)$, has been suggested by Anderson and Dillon (1991), with the recommended range in developed countries being between 1 and 2. The coefficient of relative risk aversion is related to $r(x)$ by the function:

$$r(x) = r_R(x)/w$$

where w represents wealth. If a farmer's assets are around $1 million this implies a maximum range of $r(x)$ coefficients of 5×10^{-7} to 4×10^{-6} and a recommended range of 1×10^{-6} to 2×10^{-6}. Bardsley and Harris (1987) estimated values of absolute risk aversion of 1×10^{-5}, 6×10^{-5} and 1×10^{-6} for the High Rainfall, Wheat-Sheep and Pastoral Zones of Australia respectively. The Bardsley and Harris values represent higher levels of risk aversion. A range of absolute risk aversion coefficients, based on those of Anderson and Dillon (1990) and Bardsley and Harris (1987) were used in this study. The program Generalised Stochastic Dominance developed by Raskin and Cochrane (1986) is used to apply the SDRF analysis.

3. Model Specification

3.1 Simulation model

The simulation model included both random and fixed variables of the farming system studied. Fixed variables include the farm size, soil types, irrigation layouts, institutional limits on production of some activities, labour availability and objective function values. For each drainage recirculation and on-farm storage scenario the model determined the storage size, capital, maintenance and pumping costs, and the monthly evaporation values associated with that particular storage.

The three random variables in the model are allocation supplies, off-allocation supplies and rainfall (from which rainfall runoff is calculated). Historical allocation data was obtained from a Murray-Darling Basin Commission hydrology simulation model of the Murray River. This model simulates behaviour of the Murray system assuming the current level of irrigation development and storage capacity using historical streamflow data and other physical information. The period modelled covers 96 years from 1892 to 1987. The maximum level of allocation to Berriquin over this period was 140 per cent, with a mean allocation of 119 megalitres and a standard deviation of 39 megalitres. The hydrology simulation data indicated that the probability distribution was negatively skewed (skewness -1.76 and kurtosis 4.78) implying that the function may not be normally distributed. A variety of distributions (18 in all) were tested for goodness of fit using the chi-square test. The best were logistic (χ^2 of 49.8) and normal (χ^2 of 58.7). The critical value of χ^2 at 5 per cent for 19 degrees of freedom was 30.14. As both the logistic and normal distribution chi-square values lie outside this critical value they were rejected on the basis of goodness of fit. Consequently, a cumulative distribution was used in this analysis for allocation supply.

The hydrology simulation model of the Murray River also predicted the availability of monthly off-allocation flows for the 96 year period. For each month a 0/1 value indicated the existence or not of off-allocation availability, the volumes when available being limited by the capacity of the water delivery system. For each month off-allocation was either 450 megalitres (the supply channel capacity) or 0 megalitres. The probabilities of the occurrence of monthly off-allocation flows were calculated from the hydrology simulation data and are presented in Table 1. A discrete distribution was used to specify this variable in the simulation model.

Table 1: Probability of monthly off-allocation supply availability

Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun
0.67	0.56	0.60	0.45	0.28	0.00	0.00	0.00	0.00	0.04	0.16	0.43

Daily rainfall data for the period 1968 to 1992 were obtained for the town of Finley, located within BID. This data was used to derive cumulative distribution functions for daily rainfall events in each month. The probability of rainfall for all days within a given month was assumed to be equal. Daily rainfall runoff was then calculated from the formula:

$$R = \left[\frac{(P - Ia)^2}{P + (4 \times Ia)} \right]$$

where R = daily rainfall runoff;
P = precipitation; and
Ia = initial abstraction (a function of antecedent soil moisture conditions, slope, vegetative cover and soil type).
Source: Water Research Foundation of Australia (1965)

Daily rainfall runoff values were aggregated to obtain monthly rainfall runoff. Mean monthly rainfall runoff values from the stochastic simulations for the representative farm are presented in Table 2.

Table 2: Mean monthly rainfall runoff for representative farm (megalitres)

Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun
0.32	0.29	0.31	0.69	1.10	1.17	2.45	0.89	0.53	1.35	1.76	0.52

An important point to consider when conducting stochastic simulations is the degree of dependence between the stochastic variables. If there is reason to suspect that there may be a relationship between the values of the uncertain variables then some account needs to be taken of the relationship in sampling for each variable within the same iteration.

A test for correlation was conducted between allocation and off-allocation supplies. A statistically insignificant correlation coefficient of 0.07 was determined for allocation and off-allocation suggesting that these two variables are independent of each other.

Both allocation and off-allocation supplies were expected to be independent of rainfall for both spatial and temporal reasons. Berriquin is located well to the west of the storage headworks in the upper catchments (which determine allocation availability) and to a large extent experiences different weather patterns. In addition, rainfall is experienced by farmers in the current period whereas allocation is primarily determined by rainfall in the upper catchment in previous seasons.

A test for autocorrelation in allocation supplies was conducted as the hydrology simulation data indicated a possible lack of randomness between years. A statistically significant serial correlation coefficient of 0.43 was calculated indicating the presence of autocorrelation. This is accounted for in the model by using the dependency features of @RISK™ to make allocation in iteration t of the simulation model correlated to the level of allocation in iteration t-1.

3.2 Linear programming model

The objective function of the multiperiod linear programming model involved the maximisation of whole farm gross margin. The model was used to report on a range of physical effects upon the farm system, as well as on financial performance. These include the areas of crops and rotations, total water use from various sources, levels of drainage recirculation and drainage discharge from irrigation, and watertable recharge.

Description of the model is disaggregated into two areas.

Water resources

The model specified 12 monthly time periods beginning with July and ending with June. The multiperiod approach was required so as to account for the temporal dimensions of irrigation water supply, plant evapotranspiration demands, and limitations on the drainage recirculation and water harvesting capacity of the system simulated.

The dynamics of the water management options are outlined in Figure 3. Crop and pasture evapotranspiration requirements in each month were met solely from irrigation[7]. The traditional supply of irrigation water is allocation and off-allocation (when available) supplies. The level of annual allocation can be varied by purchasing or selling water entitlement via a temporary TWE scheme[8]. With the adoption of a recirculation system, quantities of irrigation runoff and rainfall run-off can be recycled on the farm and used for irrigation purposes.

Installation of an on-farm storage system increases the capacity of the recirculation system and expands potential opportunities for water management. In conjunction with a recirculation system, irrigation run-off can be stored and recycled in greater volumes (due to the greater capacity of the storage) and can be stored for use in later periods. The on-farm storage allows the capture and storage of off-allocation supplies and rainfall runoff. Water transferred from one period to the next is subject to losses from evaporation. The study assumes that the storage is emptied by the end of the irrigation season so that sufficient airspace is available to allow the capture of off-allocation supplies and rainfall runoff in the winter and early spring months. A multiyear optimisation model is therefore not required.

When irrigation water is applied to a field crop, in addition to meeting plant evapotranspiration requirements, irrigation runoff and watertable recharge can occur to the extent that these requirements are exceeded. The level of irrigation runoff depends upon soil type, slope and irrigation layout and was expressed as a percentage of water application. Irrigation run-off could alternatively be disposed into a district surface drainage network. Each irrigated crop and pasture activity contributes towards watertable recharge, the level of which depends upon soil type, slope and irrigation layout. The recharge values were also expressed as percentages of applied irrigation water.

Rainfall runoff was modelled in the same manner as irrigation runoff, either being recirculated and used for irrigation if a recirculation system is present, or disposed of into district drainage.

When a farm neither has a recirculation system or access to district drainage, runoff will lie ponded on the farm, leading to waterlogging losses and recharge of the watertable. Alternatively, runoff may drain into neighbouring farms or roadsides, which again results in contributions to the regional watertable and waterlogging losses.

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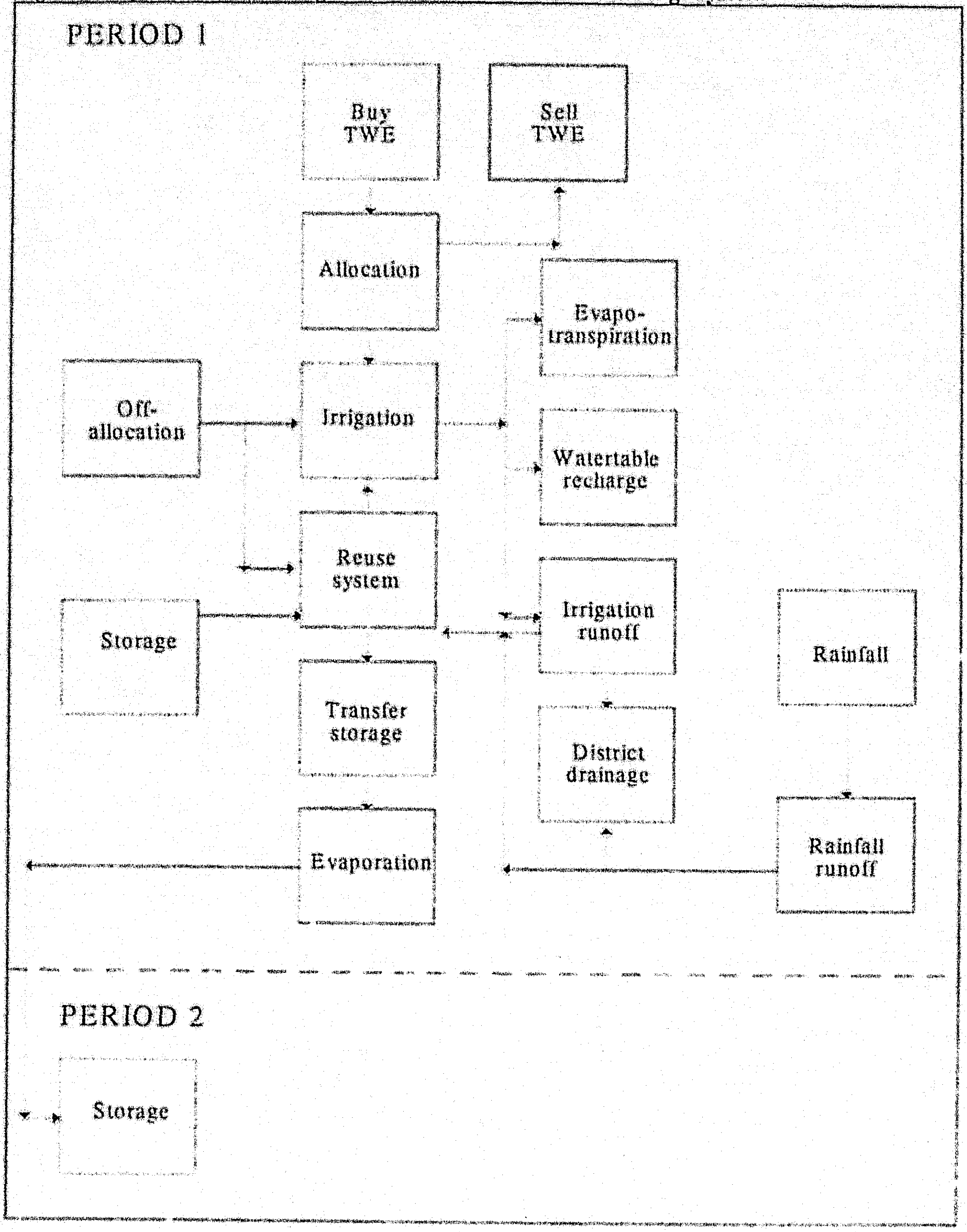
[7] As discussed in section 2.1 there is little expectation in this region of summer rainfall contributing to plant evapotranspiration requirements.

[8] Irrigators in Berriquin also have access to a permanent TWE scheme. For the purposes of this analysis it is assumed that both temporary and permanent TWEs have the same annualised values.

Figure 3: Dynamics of drainage recirculation and on-farm storage system



Agricultural activities

A representative farm was developed for what is known as a 'mixed farm' in BID. Farm size was assumed to be 209 hectares with a licensed allocation of 608 megalitres. Through adopting a whole farm systems framework the model is able to account for the complex physical and economic interactions which exist on farms in this region. Accordingly, important factors such as soil types, farm labour availability, rotation options, crop types, water use, pasture management, livestock, institutional arrangements, runoff and recharge are all explicitly accounted for in the model.

The representative farm included three soil types: sandy loam (54 hectares), loam (95 hectares) and clay (56 hectares). On sandy loam the crop and pasture enterprises included lucerne, summer pasture, annual pasture and oats. The irrigation layouts were either landformed or non-landformed border check.

On loam soils, wheat, oats, soybeans, lucerne, summer pasture and annual pasture were the primary enterprises on landformed and non-landformed border check layouts. The latter layout was further categorised as being well or poorly drained with the appropriate yield adjustments made in the enterprises. On landformed contour bay layouts, rice in rotation with wheat and annual pasture, and summer pasture were the enterprise choices.

On clay soils which were landformed border check the enterprises were lucerne and annual pasture. It was expected that no non-landformed border check layouts would exist on this soil type. The same enterprises existed on both landformed and non-landformed contour bay layouts, with the appropriate yield differences. These were rice, wheat, oats and annual pasture in rotation. On all layouts dryland annual pasture could be produced, while on areas which were non commandable for irrigation a rotation of dryland wheat and annual pasture was possible.

Each crop and pasture type utilised and contributed to various pools in the model. Water requirements were satisfied from the various water activities mentioned in the previous discussion. Labour requirements were met from farm labour available or, if more was required, casual labour could be employed. The yield from each crop contributed to various selling pools which disposed of grain at a specified value per tonne. Pasture enterprises supplied yields to seasonal pasture pools from which livestock feed requirements were met. In addition to water requirements, crops and pastures contributed to both irrigation runoff and watertable recharge which were specified on a monthly basis.

The model allowed for annual pasture to be utilised for hay as well as directly consumed by livestock. Hay making occurred in spring and could be fed out in either summer or autumn. Alternatively, annual pasture hay could be sold.

Merino wethers was the sole livestock enterprise specified in the model. Only one livestock enterprise was used so as to comply with the conditions associated with tactical risk. Wethers were used as they were a dominant livestock choice in deterministic runs of a broader ranging linear programming model of this region.

Strategic and tactical risk responses

The alternative strategies tested in this analysis are presented in Table 3. Strategic decisions which were also specified are the basic type of rotations and livestock enterprise, however, these were not varied in the analysis. A basic strategy which the study assumed remained fixed for all the simulations was that the representative farm had access to a regional surface drainage network to dispose of excess irrigation and rainfall runoff.

Table 3: Description of strategic decisions

Strategic decision	Description
0	Do nothing
1	Recirculation system only
2	Recirculation system plus 5 megalitre storage
3	Recirculation system plus 10 megalitre storage
4	Recirculation system plus 26 megalitre storage
5	Recirculation system plus 48 megalitre storage
6	Recirculation system plus 76 megalitre storage
7	Recirculation system plus 99 megalitre storage
8	Recirculation system plus 150 megalitre storage
9	Recirculation system plus 203 megalitre storage

Tactical responses were necessary to ensure feasibility in the farm plans due to the occurrence of the uncertain events. The linear programming model in each iteration had scope to increase or decrease the number of livestock, with the appropriate capital costs and realisation. The number of livestock on hand at the end of one iteration became the starting value for stock on hand in the following iteration.

The model was also able to account for changes to crop and pasture areas, making, buying, selling and feeding hay, employing casual labour, buying TWEs (annual), selling unused entitlement as a TWE, recirculating irrigation and rainfall runoff in the current period or storing for use in later periods, using off-allocation in periods of availability or storing for later use. Care was taken when specifying the tactical responses, in particular the crop and pasture rotations, so that feasibility conditions that would exist from one year to the next were satisfied. For instance, violation of this condition would occur if on a particular soil type the model had the ability to move from a rice rotation in one iteration to a double cropping rotation featuring soybeans in the next iteration.

3.3 Benefit-Cost Analysis

A benefit-cost analysis, using the gross margin probability distribution, calculated net present values (NPV) for each of the alternative strategies. The alternative strategic decisions outlined in Table 3 involve initial capital outlays with the benefits distributed over some future period. The NPV criteria is well suited for comparing projects with differing timings of benefits and costs and was used in this study for ranking the alternative strategic decisions. The general form of the NPV method is as follows:

$$NPV = \sum_{t=1}^{n}\left[\frac{S_t}{(1+k)^t}\right] - I_0$$

where S_t = the net cash receipt in year t;
I_0 = the initial investment outlay;
k = the discount rate; and
n = the projects duration in years.

In this study a stochastic NPV was calculated using @RISK™. The distribution function for whole farm gross margin determined by the stochastic analysis was used in the calculation of S_t. The net cash receipt was determined by subtracting the annual maintenance costs of the strategic decision (Table 4) from the whole farm gross margin. I_0 was represented by the capital costs presented in Table 4. The discount rate was 10 per cent and the project's duration was 30 years. No adjustments were made in the analysis for income taxation concessions.

Table 4: Capital and maintenance costs of strategic decisions

Strategic decision	Capital cost ($)	Annual maintenance ($)
Recirculation system	17,000	350
5 megalitre storage	20,091	350
10 megalitre storage	29,000	350
26 megalitre storage	33,560	500
48 megalitre storage	42,980	500
76 megalitre storage	53,720	500
99 megalitre storage	62,000	500
150 megalitre storage	93,680	1,250
203 megalitre storage	109,880	1,250

4. Results

Comparing the results of the stochastic analysis with those obtained from a deterministic approach, where expected values are used for the random variables, is a useful means of indicating if the additional costs involved with a stochastic methodology are justified in terms of more accurate information obtained. Consequently, the results for the risk neutral assumption are reported for both stochastic and deterministic approaches.

4.1 Impact of strategic decisions on gross margin

The whole farm gross margin results of the stochastic and deterministic analyses are presented in Table 5. These results indicate that the mean gross margin values from the stochastic analysis and the gross margin values from the deterministic analysis were similar, although the results from the latter approach were slightly higher for each strategic decision. This discrepancy was due to the fact that the deterministic analysis, by using expected values for the random variables, was not able to account for outliers in a distribution. In the stochastic analysis a number of observations of low water allocation were sampled due to the negative skewness of the allocation distribution and, by assuming higher water availability than was the actual case, the deterministic analysis consistently overestimated the gross margin values.

No ranking of the strategic decisions was possible using this criteria as the capital and maintenance costs of the strategic decisions were not included in the gross margin analysis.

Table 5: Gross margin values for strategic decisions ($)

Strategic Decision	Deterministic analysis	Stochastic analysis
Do nothing	75,324	74,557
Recirculation system	76,245	75,829
5 megalitre storage	77,751	77,011
10 megalitre storage	79,093	78,234
26 megalitre storage	80,654	79,885
48 megalitre storage	81,373	80,891
76 megalitre storage	82,285	81,821
99 megalitre storage	83,035	81,994
150 megalitre storage	84,368	83,194
203 megalitre storage	85,433	83,259

4.2 Impact of strategic decisions on NPV

The ranking of the alternative strategic decisions may differ according to an individual's risk preference. Consequently, the results for the assumptions of risk-neutrality and risk-averseness with regard to the strategic decisions are reported separately.

Risk-neutral

The majority of farm level analyses which assume risk-neutrality are conducted in the standard deterministic fashion, whereby the expected values are used for the random variables. The assumption of risk-neutrality can also be made when using a stochastic analysis. In this case the decision maker is solely interested in the magnitude of the expected values and has total disregard for variance. With these decision makers utility maximisation is equivalent to profit maximisation.

The results reported in Table 6 are calculated on a with and without project basis, i.e. they represent the difference in NPV between the strategic decision and the do nothing startegic decision. A NPV greater than zero indicates that the strategy is financially superior while a negative NPV means the strategic decision is financially inferior to the base case.

Table 6: Difference in NPV between the strategic decisions and the do nothing case ($)

Strategic Decision	Deterministic analysis	Stochastic analysis
Recirculation system	(7,561)	(3,288)
5 megalitre storage	(465)	4,028
10 megalitre storage	2,937	2,125
26 megalitre storage	10,884	15,124
48 megalitre storage	8,482	17,266
76 megalitre storage	6,534	17,228
99 megalitre storage	5,434	13,163
150 megalitre storage	(18,369)	(13,432)
203 megalitre storage	(23,370)	(27,656)

The deterministic analysis indicated that drainage recirculation systems with on-farm storages between 10 and 99 megalitres were financially superior to the do nothing strategic decision. A 26 megalitre storage system provided the highest returns from this approach.

Drainage recirculation systems with on-farm storage capacities between 5 and 99 megalitres were financially superior to the do nothing case when a stochastic analysis was adopted. Maximum returns were provided by a 48 megalitre storage, compared to a 26 megalitre storage for the deterministic approach.

Risk-averse

The results of the stochastic analysis for the strategic decisions are presented in (*E*,*V*) space in Figure 4. These results do not represent an efficient (*E*,*V*) set but illustrate the risk efficiency of the strategic decisions. For a risk averter, a 5 megalitre storage system will be preferred to a 10 megalitre system as it has a higher mean NPV and a lower standard deviation. Likewise, a 48 megalitre system will be preferred to a recirculation system with 76 megalitre and larger storages. The graphical analysis, however, is unable to indicate whether a 5 megalitre, 26 megalitre or 48 megalitre storage recirculation system will be preferred by a risk-averse decision maker.

SDRF was applied to the strategic decisions with the results for a number of *r*(*x*) ranges reported in Table 7. The results indicate that under the *r*(*x*) range suggested by Anderson and Dillon (1991) a recirculation system with a 48 megalitre on-farm storage is optimal for risk-averse farmers. Under the range of risk aversion reported by Bardsley and Harris (1987), risk-averse farmers would be indifferent between the adoption of a 26 megalitre and 48 megalitre storage with a recirculation system.

Figure 4: NPV results for strategic decisions in (*E*,*V*) space ($)

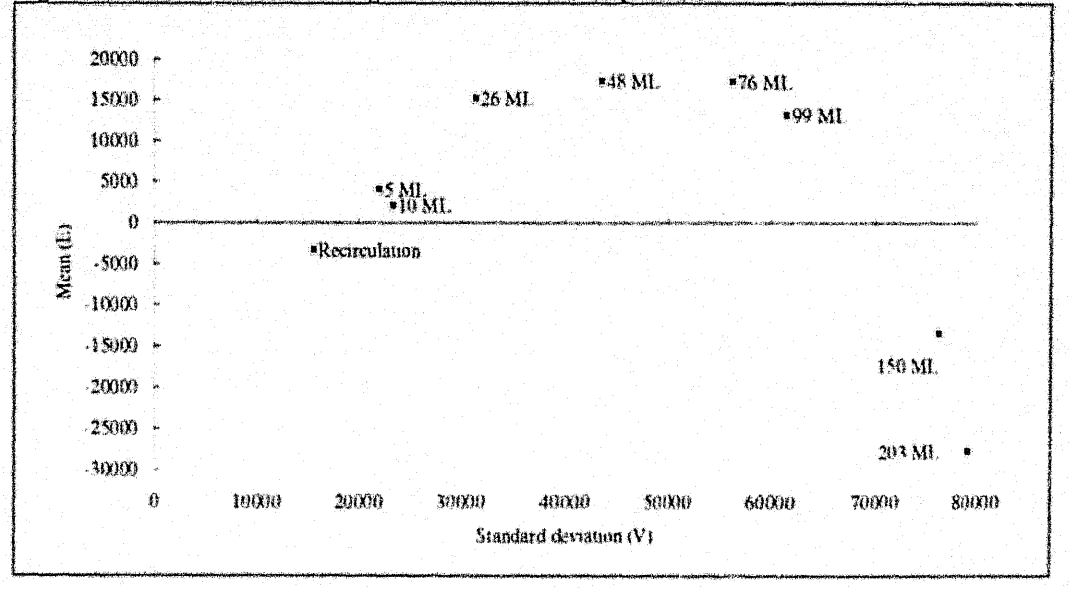


Table 7: Dominant recirculation strategies with various ranges of absolute risk aversion

Risk aversion range	Dominant strategy
1 x 10^{-6} to 3 x 10^{-6}	48 megalitre storage
1 x 10^{-5} to 1 x 10^{-6}	26 megalitre storage
	48 megalitre storage

4.3 Impact of strategic decisions on the environment

The stochastic analysis was also able to determine the mean values for a range of physical information as well as whole farm gross margin. Environmental values of interest are presented in Table 8.

The results indicated that the requirement for draining runoff off-farm diminished significantly as the size of the storage in a recirculation system increased. Moreover, recharge of the watertable from off-farm sources associated with the runoff declined as the storage size increased. Recharge of the watertable on-farm increased due to the extra irrigation involved with these strategies. Overall, the levels of watertable recharge and drainage of irrigation runoff declined with the installation of recirculation and on-farm storage systems. There are social benefits involved with the reduction in these externalities which have not been captured in this study.

Table 8: Mean environmental values associated with the strategic decisions (megalitres)

	Irrigation Runoff		Rainfall Runoff		Watertable Recharge	
Strategic decision	Stored	Disposed	Stored	Disposed	On-farm	Off-farm
Do nothing	0	125	0	16	25	16
Recirculation system	22	105	2	16	26	13
5 megalitre storage	57	71	6	12	28	9
10 megalitre storage	92	39	7	10	30	5
26 megalitre storage	133	1	11	6	34	1
48 megalitre storage	137	0	15	2	35	0
76 megalitre storage	139	0	16	1	36	0
99 megalitre storage	140	0	18	1	37	0
150 megalitre storage	143	0	17	1	38	0
203 megalitre storage	144	0	17	1	38	0

5. Summary and Discussion

The objective of this study was to assess the financial benefits associated with various on-farm drainage recirculation and storage options for a representative farm in Berriquin Irrigation District. A stochastic programming approach was adopted so as to account for uncertainty in a number of key variables; allocation supplies, monthly off-allocation flows and rainfall runoff.

The stochastic analysis indicated that risk neutral farmers would prefer a recirculation system with a 48 megalitre storage, whereas a deterministic run of this analysis determined that maximum returns were to be obtained from a recirculation system with a 26 megalitre storage. The difference in results between these approaches was due to the stochastic analysis being able to account for outlier values from the distributions which cannot be reflected in the expected values for random variables used by a deterministic approach. The stochastic analysis provided, therefore, a more accurate assessment of the benefits and costs associated with the strategic decisions studied.

SDRF procedures were applied to determine the preferences of risk averse decision makers. A recirculation system with a 48 megalitre storage was the dominant strategy for an absolute risk aversion range of 1 x 10^{-6} to 3 x 10^{-6} (suggested by Anderson and Dillon 1990), while a recirculation system with a 26 megalitre storage joined this strategy in the dominant set for an absolute risk aversion range of 1 x 10^{-5} to 1 x 10^{-6} (measured by Bardsley and Harris 1987). The results suggest that for this problem there is little difference between the preferred strategies for risk-averse and risk-neutral farmers.

The analysis indicated that the adoption of drainage recirculation and on-farm storage systems lead to reductions in the level of externalities associated with the management of irrigation and drainage water. There are social benefits involved with reductions in these external costs.

The stochastic programming methodology used in this study was an adaptation of the 'distribution problem' approach presented by Johnson, Tefertiller and Moore (1967). The main modification was the development of a stochastic simulation model which contained the strategic decisions and executed the linear programming model. For each run of the simulation model a strategic decision was pre-specified for the entire simulation, the results of the simulations were then compared to assess the alternative strategic decisions. The possible tactical responses to the initial strategic decision and intervening states of nature were confined to the linear programming model.

The stochastic modelling process was 'passive' in nature, implying that decision makers have perfect knowledge of the random events. This assumption was feasible given the nature of the climate and the irrigation supply system in the region, with uncertainty essentially being confined to water availability between years as supply and demand for irrigation water within the summer irrigation season is deterministic. If the problem was one that supply of irrigation water throughout the summer irrigation season was uncertain then this 'passive' condition would be violated and an alternative approach required, such DSP or stochastic dynamic programming. Alternatively, the methodology presented in this study could be further adapted to account for such situations. For example, the linear programming model could be used to determine farm activities and tactical responses prior to the commencement of the irrigation season, subject to the information known at that time. The simulation model would not only specify the initial strategic decisions but also allow further tactical responses to the farm plan developed by the linear programming model as certain states of nature become known as the irrigation season progressed. Such an approach could then accurately reflect the strategic and tactical responses that would be involved.

The stochastic programming formulation presented in this study has substantial flexibility in dealing with the strategic and tactical responses associated with problems involving embedded risk. The model developed is generally smaller than those using DSP for the same problem which represents a significant advantage when considering the costs of model development, verification and validation.

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