AgEcon SEARCH
RESEARCH IN AGRICULTURAL & APPLIED ECONOMICS

The World's Largest Open Access Agricultural & Applied Economics Digital Library

This document is discoverable and free to researchers across the globe due to the work of AgEcon Search.

Help ensure our sustainability.

Give to AgEcon Search

AgEcon Search
http://ageconsearch.umn.edu
aesearch@umn.edu

*Papers downloaded from **AgEcon Search** may be used for non-commercial purposes and personal study only. No other use, including posting to another Internet site, is permitted without permission from the copyright owner (not AgEcon Search), or as allowed under the provisions of Fair Use, U.S. Copyright Act, Title 17 U.S.C.*

35th Annual Conference of the
Australian Agricultural Economics Society,
University of New England, Armidale, 11-14 February, 1991.

OPTIMAL IRRIGATION WATER ALLOCATION AND SUPPLY RELIABILITY IN THE MURRUMBIDGEE VALLEY*

Randall Jones[1], Warren Musgrave[2] and Mike Bryant[3]

ABSTRACT

The objective of this study is to determine the optimal level of irrigation supply reliability in the Murrumbidgee Valley which satisfies the goal of economic efficiency. Traditionally, water supply authorities have aimed to supply irrigators full allocations in all but the most severe drought years. This means that a substantial amount of water is held in storage as a reserve and in most years is not utilised, either for irrigation or other, including environmental, purposes. In a climate where maximum economic returns for resources are required, water supply authorities are now reconsidering this policy of high reliability with a view to expanding water use for agricultural and environmental purposes.

This study uses linear programming, combined with an hydrology simulation model developed by the Department of Water Resources, to analyse various water allocation scenarios for irrigation and their associated supply reliabilities over a hundred year simulation period. The results of the study will indicate what level of water allocation and supply reliability will maximise regional net income.

* This paper is based on a study funded by the NSW Department of Water Resources. The Centre for Water Policy Research, in cooperation with the Department of Water Resources and NSW Agriculture & Fisheries, is conducting broader study of structural change in the MIA.

---

1. NSW Agriculture & Fisheries, Orange.

2. Centre for Water Policy Research and Faculty of Economic Studies, University of New England, Armidale.

3. Centre for Water Policy Research, University of New England, Armidale.

1. Introduction

1.1 Background to the problem

The reallocation of existing supplies of irrigation water is increasingly becoming an issue of importance as most Australian water economies enter a 'mature' phase of development. No longer can water be considered a cheap and plentiful resource. The marginal cost of providing additional units of this resource can be expected to increase significantly relative to that of the past as low cost storage sites have already been developed.

A number of supply and demand management measures have been proposed to aid in the efficient allocation process. The level of water allocation and the reliability of supply attached to this level of allocation is one significant supply management measure.

Although there is recognition of a case for quantitative consideration of optimal or acceptable levels of reliability for water supply systems, there has been little formal use of empirical techniques for a number of reasons. First, the need to consider optimal reliability has occurred only as Australian water economies have entered the mature phase of development and as a result existing supplies have become fully committed and the cost of developing new supplies has become more expensive. Second, complex issues are involved, particularly as public benefits may be maximised at reliability levels well below those that maximise benefits to individuals. Third, lower reliability conflicts with the original objectives of schemes justified on high reliability or as 'drought proofing' measures. Fourth, lower reliability levels may impinge on the financial receipts of water authorities and result in wide variations in receipts from year to year. Finally, the ability to analyse actual reliability issues has become possible only with recent developments in computer facilities and techniques.

No longer can the above stated impediments to studying optimal reliability of water supplies be considered to be valid. The adoption of reliability levels that maximise economic benefits will become more important as the requirements for reallocation of existing supplies increases.

The Murrumbidgee Valley is a major irrigated region in southern NSW which has traditionally had a much higher reliability of supply of irrigation water than other irrigated river valleys. This raises the question as to whether the provision of such a high level of water security has been at the expense of having an overall level of irrigation development that is lower than socially optimal. The purpose of this paper is to address this issue.

1.2 Objectives and hypotheses of the study

The basic objective of the study is to determine the level of supply reliability and allocation in the Murrumbidgee Valley which satisfies the goal of economic efficiency. The following hypothesis is tested.

* the current level of supply reliability and allocation is optimal.

If this hypotheses is rejected the optimal levels will be determined. The hypothesis involves examining the trade-off between a system with high reliability but lower average regional benefits to a system with low reliability but higher average regional benefits. The variance of returns in the latter situation is expected to increase significantly, so a long time horizon is necessary to do it justice.

1.3 Outline of the study

The following section introduces some of the important economic issues involved in the efficient allocation of resources, particularly irrigation water. In addition, a number of definitions of reliability are presented. Section 3 presents the theoretical framework that is used in this study, which revolves around the concept that there are trade-offs involved in systems with differing reliabilities. The methodology used is contained in section 4, with attention given to the determination of the appropriate objective function. Section 5 indicates how the irrigation development scenarios are determined while the results of the study are presented in section 6. The study concludes that economic efficiency can be improved with a higher irrigation development level and lower supply reliability than the current level, but there are distribution consequences.

2. Economic issues in efficient water allocation

A regional water economy can be characterised as being in an "expansionary" or a "mature" phase (Randall, 1981). In the expansionary phase the marginal cost increments in water supply rise only slowly over time, if at all. The water economy operates on the very elastic segment of the supply curve for suitable sites for water impoundments, river modifications, and irrigation developments. As the demand for water shifts rightward, existing surplus capacity is utilised or new projects can increase the quantity supplied with little increase in real average cost. A feature of the expansionary phase is the public subsidisation of resource development projects, provided the political environment encourages such projects. As the stock of water impoundments and irrigated lands is in a

new condition, problems of reservoir siltation, rising water tables, salt damaged lands, and saline return flows into river systems remain relatively insignificant. Competition for water among the various users (agricultural, urban and recreational) is not a significant issue as demand can be alleviated by new projects. The chief concern of public economists during this phase is determination of the appropriate rate of expansion of the water economy and the appropriate degree of subsidisation of the water economy.

The expansionary phase eventually must come to an end and the water economy then enters a mature phase. The water economy is now characterised by sharply rising incremental costs of supplying water, and greatly increased interdependencies among water users. There is more intense competition for water supplies which expand slowly, and the aggregate effects of individual water use decisions include rising water tables and increasingly polluted and saline effluents.

The Murrumbidgee Valley is typical of a region which has undergone an expansionary phase since its development in the early part of this century, but has now entered a mature phase where there is now considerable conflict between agricultural, urban and recreational users, there are significant problems of water pollution and land degradation, and there is a need for rehabilitation of aging reservoirs, water delivery and drainage systems.

The issue of reallocation of existing supplies is an area of major concern to water supply planners. Randall introduces two approaches; water pricing and markets in water.

A major concern of economics in water pricing relates to the issue of marginal cost pricing in decreasing-cost and increasing-cost systems. For a given water delivery system of fixed capacity, marginal delivery cost is relatively low and fairly constant until the capacity constraint is approached. On the other hand, the fixed costs of such a system are quite high. The average delivery cost continues to decrease until the capacity constraint is approached. This has resulted in the erroneous conclusion that water delivery is a decreasing cost industry. As the demand curve for water moves to the right, quantity demanded eventually exceeds the capacity of the delivery system. New larger delivery systems are required and it is therefore likely that the long-run marginal cost of water is increasing rather than decreasing.

The efficient allocation of water requires that the marginal units of water delivered be priced at their marginal cost. Randall notes that while it should be possible for a water authority to design a pricing system which adequately equates resource cost and opportunity cost of water at the margin over the long-run while raising sufficient revenue to cover the total costs of water delivery, there are two disadvantages. First, there is a high cost of adequate information, especially in a dynamic and stochastic world. Second, there are inevitable

political pressures brought to bear upon the authorities in an attempt to divert it from its water pricing goals in pursuit of other social and political objectives.

Establishing a market in delivered water, which focuses on opportunity cost rather than resource cost, is an alternative to efficiency in water resource allocation. A marketable water right market would result in the pricing of water to users at its opportunity cost.

Marketable water rights would institute water entitlements as legal property instruments, vested in the individual and negotiable independently of the land. The specification of entitlements should recognise the fundamental variability of supply and demand.

There are two advantages of a market in water entitlements to a resource cost pricing policy. First, centralised information costs would be reduced, as the market would tend to generate the necessary information and market users would bear the information costs. Second, a system of marketable rights to water deliveries would correct a wide range of allocative deficiencies which may be inherent in any particular pricing policy followed by authorities.

Demand management measures to improve the efficiency of water allocation has received a great deal of attention from economists, as illustrated in the previous section. Supply management measures, particularly reliability of supply, can also play an important role in the allocation process. Knowledge of the optimal reliability of a regulated river basin under the control of the supply authority will allow planners to identify those basins where major water allocation and supply mismatches occur (Verdich and Bryant, 1986). An inappropriate irrigation supply reliability in a river basin may mean a net social loss of millions of dollars per annum.

Water supply systems are typified by stochastic supplies and demand in that knowledge of climatic, hydrologic, economic and social behaviour, and predictions regarding future performance are always subject to error. A failure state is defined as one in which stochastic system performance levels are judged to be unsatisfactory (Kuczera, 1987). Reliability of irrigation supplies is one measure of system failure.

There are a number of definitions of reliability. Hashimoto et al (1982a) define reliability as the frequency or probability, α, that a system is in a satisfactory state:

$$\alpha = Prob\ [X_t \in S]$$

Where X_t is a systems output state, and S is a set of all satisfactory states. Dudley (1975) defines a reliable system as being one in which farmers receive the quantities of water they desire at the usual price in a large percentage of

seasons. Another definition of reliability is the probability that no failure occurs within a fixed period of time, often taken to be the planning period (Hashimoto et al). An additional definition of reliability is one minus the probability of needing to reduce irrigated crop area below the maximum area possible, either by planting a lesser area at the start of the season or by abandonment to rain fed status during the year.

In this study supply reliability is taken to be the percentage of years that irrigators receive their full allocation (ie 100 per cent). Supply reliability is only a measure of the frequency of years that full allocation occurs, it gives no indication of water availability in those years which have less than full allocation. A measure called 'average allocation' percentage (average of actual announced allocation) adequately describes the availability of irrigation water.

Supply reliability is a function of stochastic supply and demand influences. The demand for water may be considered in terms of the total volume to be supplied over a given period, which may be daily, weekly or annually. Demands for irrigation water can vary from one period to the next due to climatic influences (wet periods particularly reduce the demand for irrigation water), and the mix of crops grown in response to various market forces. Some crops, such as rice and lucerne, have significantly higher water requirements and any changes in their total area will affect overall irrigation water demand. The main source of uncertainty in supply of irrigation water are seasonal conditions. The seasonal effects can have temporal implications, for instance, a period of drought can seriously affect irrigation supplies in following seasons due to a possible drawdown on water storages.

Alternative supply reliabilities can have differing impacts upon individuals and the state economy. An individual farm income is related to water supply reliability; as the reliability of irrigation supply decreases, average annual farm income decreases and income variability increases. As the total volume of licensed allocations increases there is a corresponding decrease in supply reliability, however from a state economy viewpoint there is an overall increase in average annual income.

Howe (1990) identifies a number of criteria by which allocation institutions might be assessed. These are:

(a) flexibility in the allocation of existing water supplies;
(b) security of tenure for established users;
(c) confronting users with the real opportunity cost of the resource;
(d) predictability of the outcome of the process;
(e) equity and fairness in the allocation process; and
(f) the allocation process must be capable of reflecting public values that are not considered by individuals.

A system of property rights which satisfies these criteria would be 'non-attenuated', in other words they would be fully specified, they would be exclusive, they would be enforceable and enforced, and they would be transferable.

Knowledge of the optimal level of reliability is an essential requirement for the specification component of a non-attenuated set of irrigation water rights. Determination and implementation of an optimal water supply reliability is viewed as a complementary, rather than a substitute, measure to marketable water rights and marginal cost pricing to obtain a Pareto-improvement in the Australian water economy.

3. Trade-offs involved with differing supply reliabilities

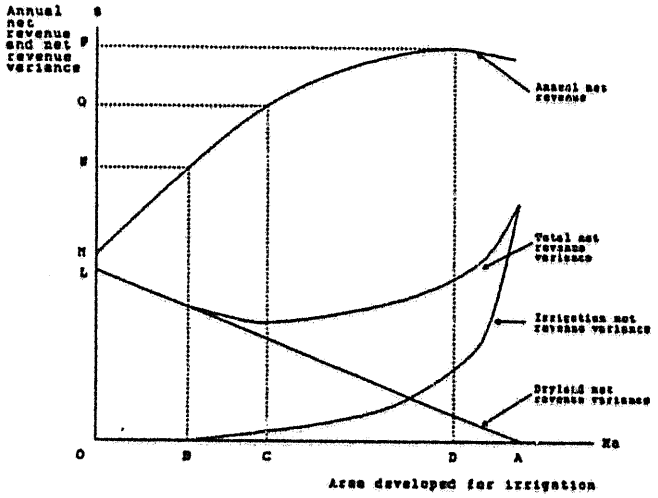
Traditionally, water supply authorities have aimed to supply irrigators full allocations in all but the most severe drought periods. Drought proofing of agriculture has been a common justification for the establishment of irrigation schemes in Australia (Davidson, 1969). This means that as high a degree of reliability of water supply as possible has been maintained. An alternative way of expressing this objective is that authorities have attempted to minimise the revenue variance of irrigated agriculture. This clearly advantages the irrigators who are currently within the supply system, but may be at odds with the overall goal of economic efficiency.

Davidson states that irrigation has failed in its objective to stabilise production during drought, as the decline in irrigated production during drought is just as severe as that in dryland areas. Davidson comments that "a policy of optimising returns from irrigation schemes can only be achieved if the policy of attempting to supply farmers with irrigation water during drought periods is abandoned. The two aims of maximum economic efficiency and drought prevention are mutually exclusive". If the state's aim is to maximise economic efficiency, the optimum irrigation area should be calculated and a flexible system adopted of selling water which does not attach a definite amount of water to any particular piece of land. The optimal area must be allowed to adjust to changes in price levels, costs and technology if economic returns are to be maximised in the long run.

Dudley (1975) determined that average annual net revenue could be approximately doubled by moving from the area at which revenue variance was minimised to a much larger area at which average annual revenue was maximised.

The trade-off problem as presented by Dudley is illustrated in Figure 1. The area developed for irrigation is represented on the horizontal axis while the annual net revenue and net revenue variance are shown on the vertical axis. The area *OA* represents the maximum area that can be developed for irrigation, and *OM* and *OL* are the annual net revenue and net revenue variance if the total area of *OA* remains in dryland use. The line *LA* represents the linear reduction in dryland revenue variance as irrigation replaces dryland production. As the irrigable area increases from zero, annual net revenue increases linearly (irrigation variance is close to zero and thus total variance falls) until a point is reached, at area *OB* and average net revenue *ON*, where the irrigable area is so large that water shortages occur in some dry seasons. As irrigable area expands beyond *OB*, the annual net revenue curve is no longer linear as irrigation variance becomes non zero. The irrigable area could be expanded to *OD* where maximum annual net revenue occurs at *OP*, however the irrigation net revenue variance is increasing rapidly at this point. This indicates a very unreliable water supply as total net revenue variance is also increasing rapidly. Total net revenue variance is minimised at *OC*. The rational zone for the irrigable area must lie between the range *OC* to *OD* as both total revenue variance and annual net revenue are increasing between these two points. The choice of the appropriate irrigable area depends on the decision maker's trade-off preference between increasing average net revenue and net revenue variance.

Figure 1: Trade-offs between high and low reliability systems



4. Methodology

4.1 Study procedure

The study uses a combination of simulation, linear programming and spreadsheet models to analyse allocation and supply reliability issues in the Murrumbidgee Valley with the aim of determining optimal policies. The way in which these models interact for the purpose of this study is presented in Figure 2.

Reliability of supply is altered by varying the level of water allocation and licensed area for irrigation in the Valley. As the level of allocation and licensed area increases supply reliability will decline, however there will be a corresponding increase in annual net revenue and a corresponding increase in total net revenue variance. An allocation level will be reached which gives the highest average annual net revenue (calculated over a 99 year period), and the supply reliability which corresponds with this development level will be deemed optimal. At areas of development greater than this amount, total net revenue variance becomes so great as to result in a decline in average net revenue.

Deterministic linear programming is used to calculate optimal annual net returns from irrigated agriculture for a variety of water allocation scenarios. Linear programming has been chosen in preference to dynamic programming and nonlinear programming techniques principally because of the "dimensionality" problem associated with these methods. Further, the demand for irrigation water is considered to be deterministic so only the stochastic supplies need to be captured and this is done through the simulation model. Support for this approach is provided by Dudley (1990).

Dudley suggests that there are two Australia's, one lying in the predominantly winter rainfall zone of the higher latitudes, and another covering the predominantly uniform and summer rainfall zones in the lower latitudes. In the winter rainfall zone the summers are very dry, which means that rainfall contributes little to the summer water requirements of plants and the total summer evapotranspiration does not vary much from year to year. From a decision making viewpoint, once the pre-irrigation is applied there is virtually no uncertainty of either demand or supply for the immediate year. Uncertainty is essentially limited to supply in later years. Known supply and demand for the immediate season permits the use of deterministic, season-long computer-based operations research methods, such as simulation or linear programming models, with a high degree of confidence.

The Murrumbidgee Valley is typical of a higher latitude, winter rainfall zone, and thus the use of deterministic linear programming to calculate net benefits and optimum farm programs is appropriate given the above discussion.

A hydrology simulation model of the Murrumbidgee Valley has been developed by the Department of Water Resources (DWR), which contains 99 years of streamflow and hydrological data from 1891 to 1989. This model is used to generate annual announced allocation percentages for various levels of irrigation development (5 per cent increases from the current level), which result in differing supply reliabilities.

Four regional linear programming models are developed to determine regional net farm income (NFI) which is used as a measure of annual net revenue, and agricultural activity levels. The models represent the Murrumbidgee Irrigation Area (MIA), Murrumbidgee Irrigation Districts (MID), Coleambally Irrigation Area (CIA), and private diverters who pump directly from the river. Each of these models are solved for different allocation levels (0 to 120 per cent in 5 per cent increments), with the results being transferred to a third model, a spreadsheet. In addition to changing allocation levels, the private diverters model will also have the level of allocation and licensed area altered. Licensed area and allocation are increased from the current level of development (92 per cent usage of current licensed allocation) to 150 per cent of current licensed allocation. Development is increased in 5 per cent increments up to this level. This results in 12 individual linear programming models for the private diverters region, making a total of 15 models required to be solved for the entire study.

There is very little potential for increased allocations and irrigation development in the irrigation areas and districts due to a lack of suitable land that can be irrigated by gravity flow, restrictions on channel supply and drainage systems and the capital costs involved. Therefore, the realistic assumption is taken that any further irrigation development undertaken in the Murrumbidgee Valley will be private development along the river.

The spreadsheet acts as an accounting procedure, which combines the results of the hydrology simulation and regional linear programming models to calculate average regional NFI. The linear programming models give the NFI for the various allocation percentages and this is set up as a table in the spreadsheet. The hydrology model results in a range of annual allocation percentages over the 99 year period for each allocation and licensed area scenario. The spreadsheet model calculates the annual NFI over the simulation period for each allocation scenario and determines the mean and standard deviation over the sample period. The optimal reliability is determined by comparing the mean NFI's.

There are a couple of limitations involved with this approach. Firstly, the analysis implicitly assumes that decision makers are risk neutral. If in fact farmers are risk averse then the activities chosen and the NFI may be different to that of risk neutral farmers.

Secondly, by adopting static linear programming, the analysis assumes that the agricultural plans for each irrigation season are independent of the preceding

season. This may not be strictly correct as due to the rotational nature of agricultural production, activities grown in one year may not be independent of the previous years cropping program. Methods that can be used to overcome this problem include dynamic and recursive programming. Dynamic programming would be computationally difficult due to the number of state variables that may be required which leads to problems with dimensionality. Verdich and Bryant (1986) adopted recursive programming in a study of optimal supply reliability of representative farms in the Namoi Valley and MIA. The two models were run over a 21 year period from 1961 to 1981. This approach was not considered feasible for this particular study due to the computational difficulties that would be incurred. In this analysis the period of study is 99 years, with the 15 separate linear program models being required to be solved for each year this would result in a total of 1,485 solutions needed for a single set of results. The approach that has been taken in this study is a computationally easier task, even though it involves 425 model solutions to provide a set of results.

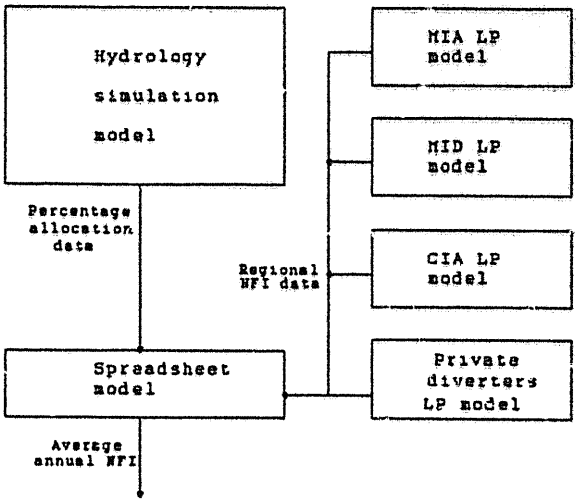
The independence problem is not as severe in practice, however, as may at first be imagined. With the exception of summer cropping programs (soybeans, sunflowers and maize), irrigation seasons can to some extent be seen to be independent of each other. Although farmers face a wide range of rotation choices, in the irrigation areas and districts rotations generally revolve around rice, wheat and pasture. Most farmers do not adhere to specific rotations but tend to vary the areas they sow to these three activities each irrigation season in response to various market forces and water supply conditions. Irrigated winter pasture represents the largest area sown in the Murrumbidgee Valley. The decision as to what area to commit to irrigated winter pasture is usually made in February and is a function of the amount of water (and land) available, with non-irrigated land generally becoming dryland pasture. This is a within season decision and is for the most part independent of the preceding irrigation season.

The Murrumbidgee Valley is an extremely complex system and a number of simplifying assumptions have to be made to avoid computational difficulties. The general assumptions that are used in the study are as follows:

(a) 1 decision maker;
(b) multiple irrigated and dryland crops;
(c) 2 reservoirs;
(d) no significant distribution system or on-farm storage;
(e) tributary flows are included;
(f) winter rainfall;
(g) deterministic demand for water with annual decisionpoints (ie. crop and water use decisions are made once per year);
(h) stochastic supply of water;
(i) irrigation products from the region are assumed to have perfectly elastic demands and constant prices;

(j) no return flows;
(k) no transferability of water between users;
(l) constant water use technology; and
(m) crop growing conditions are assumed constant across years.

Figure 2: Model procedure



4.2 Defining the objective function

The preferred choice of objective function is one that maximises net social benefit. This implies that consumer and producer surplus' are measurable. Previous studies in the area of optimal water allocation have often opted for an objective function which maximises net return to the valley or region (eg. Dudley, 1972), which may not always equate with the social optimum. Whether this is so will obviously depend upon the elasticities of the market supply and demand curves that a region faces. It is argued that in the Murrumbidgee Valley maximising net regional income is consistent with maximising net social benefit.

4.3 Regional linear programming models

The optimising models employed in this study are static deterministic regional linear programs of the Murrumbidgee Valley. The purpose of these models is to determine the optimal return and production activities for a given allocation level. A single decision maker is assumed to operate the reservoirs and make decisions regarding the areas of crops to plant. Decisions on irrigation strategies are also assumed to be made at the beginning of the irrigation season under complete certainty. By adopting deterministic linear programming, it is implicitly assumed that decision makers are risk neutral and their sole objective is the maximising of profits. The limitations of linear programming such as perfect divisibility, linearity, additivity and so on are well discussed by Hardaker (1974).

In the transition from the farm to the regional level of analysis, aggregation bias arises because all farms are not alike. Ideally, the model should be constructed for every individual farm and all the individual models linked together to form the regional model. In this case the aggregation would be exact. This option is not feasible due to the obvious computational problems that are involved. A representative farm approach is required which involves classifying the universe of farms into a smaller number of homogenous groups and constructing a model for a "representative" farm from each group. Aggregation bias will be minimised if farms are classified into groups or regions which are defined according to rigid theoretical requirements of homogeneity.

The approach taken in this study is to develop individual regional models for each of the irrigation areas, irrigation districts, and the private diverters who pump their irrigation requirements directly from the river. Within these areas, additional homogenous areas are identified and are specified on the basis of land and soil type, crop types, water allocation, and irrigation technologies. The various models are now discussed.

4.3.1 Murrumbidgee Irrigation Area model

The MIA consists of two irrigation areas, Yanco and Mirrool. These two irrigation areas are sufficiently homogenous in terms of average farm size and other resource endowments to justify their aggregation into a single group. There are two principal soil types in the MIA, red brown earths and grey self mulching clays. However, identical crop yields can be obtained on both soil types with minimal changes in crop management so there is no need to specify homogenous farm types based on soil type. Differences in irrigation technology are major determinants of yield differences in crops and pastures. Laser controlled landforming is the major adopted advanced irrigation technology on large area farms in the Murrumbidgee Valley, therefore land is separated on the basis of whether it is landformed or still in the original non-landformed contour

bay layout. Dryland areas are distinguished from irrigable land. For environmental reasons, rice areas are currently restricted to 71 hectares per farm by the DWR in conjunction with the Rice Industry Co-ordination Committee (RICC). Therefore, there is an absolute limit in the MIA to the area on which rice can be grown.

Other constraints apply to certain restrictions on some crops, annual water allocation, monthly channel supply capacities, and labour. Operators labour is specified on a seasonal basis. The seasonal labour available has been obtained from Ryan (1969), which is an average per farm multiplied by the number of farms in the MIA to give a regional labour supply. In addition to the above restrictions, constraints also apply to crop selling pools, pasture supply pools, crop-pasture rotation ties, and fixed costs.

Crop activities are presented in a rotational form. This approach has been adopted because of its simplicity and flexibility. In the Murrumbidgee Valley not only is there a wide range of agricultural activities that can be produced, but there are a wide range of rotational choices which involve the same crops. For instance, typical rice-wheat-pasture rotations can have up to three years rice, which may be followed by up to two years of wheat, and/or up to four years of irrigated winter pasture. These alternative rotations can have significant differences in their irrigation requirements and must be included in the model specification.

Separate rotations have been specified for landformed and non-landformed areas, although for the most part the rotations are the same but the yields and other technical coefficients differ. Irrigated pasture follows a cropping sequence via the pasture-rotation tie constraints. This means that a crop rotation will be followed by either 2, 3 or 4 years irrigated winter pasture phase. There is also the possibility of dryland winter pasture being grown on non-irrigated areas. Pasture is supplied on a seasonal basis in livestock months (LSMs), with the possibility of unused production in spring being transfered to summer at a 30 per cent efficiency. Hay can be made from irrigated winter pasture in spring and fed out in either summer or autumn. Livestock demands are represented by a number of sheep activities which include merino self replacing, prime lamb production (both first and second cross) and wethers. These draw their feed requirements (LSMs) from a seasonal feed pool, however only merino self replacing and wethers can utilise dryland pasture. Crop selling activities apply to rice, soybeans, maize, sunflowers, wheat, barley, canola and vegetables. Labour requirements in excess of that provided by operator's labour can be obtained by hiring casual labour. Irrigation water is obtained by a water buy activity.

The objective function of the linear programming model is the maximisation of regional net farm income.

4.3.2 Irrigation districts model

This model comprises the irrigation districts of Benerembah, Tabbita and Wah Wah. The major differences between the districts and irrigation areas are that in the districts no surface drainage is provided, farms are generally larger, and have a lower percentage of irrigable area landformed. Channel capacities are also smaller as these areas lie at the end of the supply system. Finally, water prices are lower due to the poorer quality of irrigation water. Therefore, the districts are sufficiently different to the MIA in regards to resource endowments and production possibilities to justify being modelled separately. Benerembah and Tabbita Irrigation Districts are combined together in the model while Wah Wah is specified separately. Tabbita is a small irrigation district located just to the north of Benerembah and has similar soil types, crop yields and farm sizes to Benerembah. Thus, the two districts are sufficiently homogenous to be treated as one. Wah Wah, on the other hand, differs from the other two districts as it has poorer soil types, lower yields, larger farm sizes, a more significant dryland area, and has a smaller proportion of irrigable area which is landformed.

As for the MIA model, areas that are landformed are specified separately to non-landformed areas. The remaining constraints, activities and objective function are similar to that discussed for the MIA model.

4.3.3 Coleambally Irrigation Area model

The CIA is located on the southern side of the Murrumbidgee River and has significant differences in resource endowments to the MIA. A diverse range of soil types exist in this area and it is necessary to determine homogenous areas based on this resource. For environmental reasons, soil types in the CIA are classified as being either suitable, marginal or unsuitable for rice. In the former category, no restrictions apply to rice cropping. If land is marginal, rice is limited to one crop every four years, and if it is termed unsuitable then no rice production is permitted. The last group of soils has a lower clay base and is of a sandy nature which can lead to significant accessions of applied irrigation water to the groundwater system when water is ponded during rice production. This contributes to the phenomenon of rising watertables and the associated waterlogging and soil salinisation problems that ensue. Land is again separated on the basis of being landformed and non-landformed. In addition to the above soil classifications, there is a 75 hectare rice restriction per farm set by the RICC. The remaining constraints and activities are similar to the MIA and MID models.

4.3.4 Private diverters model

This model encompasses all irrigators who pump their irrigation requirements directly from the river and do not rely on public funded channel supply systems. The area involved is along the Murrumbidgee River from Burrinjuck Dam downstream to the confluence with the Murray River and includes what are known as the distributaries, such as Yanco and Billabong Creeks, which break off from the main river. Agricultural production along the river differs markedly from the irrigation areas and districts in that it is principally pasture based and, importantly, no rice production occurs[1]. Small areas of cropping do occur along the river but, as over 80 per cent of irrigated land is planted to irrigated pasture, these activities are primarily represented in the model.

For the purposes of this study the river has been divided into four zones. This is due to significant differences in farm sizes, licensed irrigation area as a proportion of total farm area, pumping capacity (the ability to draw water from the river per month), and pasture yields between the "wetter" eastern portion of the Murrumbidgee Valley to the "drier" western portion.

Gumly Gumly Irrigation District, situated near Wagga Wagga, and Hay Irrigation Area are both included in the private diverters model. These are extremely small irrigation regions both in terms of licensed area and water allocation. Therefore, it was not considered worthwhile to model these areas separately.

Zone 1 is from Burrinjuck Dam to Narrandera. Farms are on average significantly smaller than the rest of the Murrumbidgee Valley, averaging 810 hectares with a licensed area of 58 hectares. Pumping capacity is 50,179 megalitres per month.

Zone 2 is from Narrandera to Hay. This zone is typified by large farms of 6,070 hectares with a 425 hectare licensed area, thus having a substantial dryland area. Pumping capacity is 377,405 megalitres per month which is the highest of all zones.

Zone 3 is from Hay to the Murray River. This zone has the same average farm size as Zone 2 and a licensed area of 480 hectares. What differentiates this zone from the previous one is the much lower pumping capacity of 69,669 megalitres per month and the fact that dryland pasture production is lower.

Zone 4 is the distributaries. Farm sizes average 1,215 hectares and licensed area average 162 hectares. Pumping capacity is 109,414 hectares.

---

1. In recent years moves have been made to deregulate areas where rice can be grown. Therefore, this is a crop which may be planted to some extent along the river in the future.

Activities are based on irrigated winter and summer pasture, and small areas of winter cereals and summer crops. Additional activities are hay making and feeding, seasonal feed transfers, water purchases, livestock, labour and farm overheads. The discussion of these activities is the same as with the MIA model and does not need to be repeated here.

4.4 Hydrology simulation model

The hydrology model used in this study was developed by the DWR to simulate the behaviour of the Murrumbidgee system, and to assess the effect of various operational and licensing changes on the behaviour of the system. The "performance" of the Murrumbidgee system as simulated is judged mainly by the following parameters:

(a) Announced allocation percentage. The volume of water available for allocation to Murrumbidgee irrigations at a particular time is compared to the volume of licensed irrigation in the valley.

(b) Allocation reliability. Reliability of allocation is a measure of the chance of obtaining a stated allocation percentage. It is calculated as the percentage of years that the stated allocation is available over the period simulated.

The availability of streamflow data determines the period over which the simulations can be carried out. Flow data has been recorded on the Murrumbidgee system at Gundagai, Wagga Wagga, Narrandera, Hay and Balranald since the 1880s. The period of simulation that is used is from May 1890 to April 1989, comprising 99 irrigation seasons. The model uses a simulation time step of one month.

4.4.1 Model data

The capacities of the headwater storages are 1,026,000 and 1,631,000 megalitres for Burrinjuck and Blowering Dams respectively. The natural inflow to Blowering Dam is augmented by releases from the Snowy Scheme, consisting of a guaranteed volume of 1,026,000 megalitres each season should it be required. Blowering Dam is operated to maintain an airspace of 190,000 megalitres to enable releases from the Snowy Scheme for electricity generation purposes. The Murrumbidgee irrigators are compensated for the reduction in storage capacity by the provision of a compensation reserve in Lake Eucumbene.

The model uses the following flow series as inputs:

(a) Burrinjuck Dam inflows;
(b) Blowering Dam inflows;
(c) tributary flows below the headwater storages to Gundagai;
(d) tributary flows between Gundagai and Wagga Wagga;
(e) Tumut River tributary flows below Blowering Dam; and
(f) Billabong Creek tributary flows.

Burrinjuck Dam inflows are adjusted for the effects of the Snowy Scheme. That is, it is assumed that the Snowy Scheme would have been operational for the entire period of simulation. Blowering Dam inflows are derived from simulation studies of the Snowy System for the period prior to 1968 (when the dam was completed). For the remainder of the simulation period, recorded Blowering inflows are used.

4.4.2 Model procedure

At the start of the irrigation season the simulation model runs through the following questions.

(a) How much water is in storage?
(b) How much can be allowed for inflows?
(c) What fixed and high priority commitments must be allowed for? The fixed commitments include losses, town water, riparian, stock and domestic, and end of river flows.
(d) How much water is to be allocated? This is for the Murrumbidgee Irrigation Areas and Districts, Coleambally Irrigation Area, Hay and Gumly irrigation areas, and river pumpers.

The month by month resource assessment adjusts water supplies for evaporation and rainfall, inflows to storages, usage, and utilisation of tributary flows.

The announced allocation percentage is derived by comparing the volume available for allocation to the licensed irrigation commitment. The following general conditions apply to allocation announcements as assessed in the simulation model.

(a) Allocations are announced as even multiples of 5 per cent.
(b) Allocations cannot exceed a specified maximum amount (120 per cent in recent seasons) or be less than the specified minimum.
(c) Allocations cannot decrease at any time during the season.
(d) Allocations do not increase after a certain point in the season, normally adopted as the end of March.

The simulation model uses estimated total monthly demands for the Murrumbidgee system, based on four different climatic conditions; drought, dry, medium and wet. The demands provide for the following areas:

(a) Murrumbidgee Irrigation Areas and Districts;
(b) Coleambally Irrigation Area;
(c) private diverters;
(d) town and riparian stock and domestic water supplies;
(e) Yanco, Colombo, Billabong Creek District, Hay Irrigation and Gumly Irrigation District;
(f) transmission loss allowance; and
(g) Balranald minimum flow target.

The demands for (a), (b), (c) and (e) are subject to restrictions when water shortages occur.

The tributary flow between Gundagai to Wagga Wagga is used as an indicator of the prevailing climatic conditions as it tends to integrate the effects of rainfall and antecedent wetness which determines soil moisture levels and hence crop water requirements. The model looks up a data file of tributary flows in order to be able to select a climatic condition upon which the demand for the current month is based.

Water losses throughout the system may be grouped into three types; storage evaporation, transmission, and operation. Storage evaporation and transmission losses are lost to the system while, with operation losses, the model assumes that this may be used downstream of the point of demand or flow through the system and appear in the end of system flow. These losses are discussed as follows:

(a) Storage evaporation loss. The net evaporation loss (evaporation less rainfall) used in the simulation model is mostly derived from recorded measurements of pan evaporation and rainfall. However some of the evaporation data for the early period in the simulation was derived by correlation and methods involving temperature records.

(b) Transmission loss. The transmission loss is adjusted climatically in the same way as are irrigation demands for each month of the year.

(c) Operation loss. There are two components of operation loss, rain rejection and over-ordering. Allowance is made in the model for release of water from storage for irrigation and resultant non-diversion because of rain. In the adjustment from drought demand to rain reduced demand (as predicted by the monthly demand for a particular climatic condition) it is assumed that in unrestricted periods (allocation greater than 100 per cent), 25 per cent of the rain reduction is released from storage and becomes operation loss. This implies that rain rejection occurs for 25 per

cent of the month. Secondly, in periods when the restricted drought supply is less than the rain reduced (climatic) demand, only the restricted supply is released. Thirdly, the rain reduction is calculated as the difference between the restricted drought and the unrestricted climatic demand.

In periods of unrestricted supply, over-ordering is calculated as 10 per cent of irrigation demand. During periods of restriction, over-ordering is 5 per cent of irrigation demand.

80 per cent of the operational loss is assumed to be available for diversion into Tombullen or Hay Weir, subject to channel capacities and storage capacities. Water can flow both into and out of re-regulating storages within the one month, as the simulation model calls on the re-regulating storages to supply irrigation water.

A number of assumptions have been made in the model regarding tributary flows. First, 90 per cent of tributary flows below the dams to Gundagai can be utilised. Second, between 50 and 90 per cent of the tributary flow between Gundagai and Wagga Wagga can be utilised, depending on the magnitude of this flow.

The operation of Blowering Dam in the simulation model is based on a monthly target volume, to accommodate electricity generation from the Snowy Scheme. Pre-releases made to provide airspace are limited by Tumut River channel capacity below the dam. Monthly airspace targets are calculated as follows; the airspace target in Blowering of 190,000 megalitres is increased by the excess of Blowering Dam inflows over releases during April, May and June of each year.

The model records a credit in the pre-release accounts (which is the account controlling what is known as the compensation reserve) whenever a pre-release is made to achieve airspace in Blowering Dam. This credit is limited to the maximum airspace volume of 190,000 megalitres. The simulation program calls upon this credit when there otherwise would be a storage failure in Burrinjuck and Blowering Dams. There is no airspace operation of Burrinjuck Dam in the model. The two storages are operated in harmony, with Burrinjuck drawn down 250,000 megalitres ahead of Blowering where possible to achieve the general aim of minimising spills from the system.

5. Derivation of irrigation development scenarios

As irrigation development[2] increases throughout the Murrumbidgee Valley the reliability of supply will tend to decline. The effect of these lower reliabilities was studied by varying irrigation development from the current level (92 per cent usage of current licensed allocation) to 150 percent development of current licensed allocation. The hydrology simulation model was used to provide annual allocations for the 99 year period from 1891 to 1989. The data obtained related to irrigation development levels of 92 per cent, and from 100 to 150 per cent at 5 per cent increments.

Irrigation development is accomplished by increasing the licensed allocation in the Murrumbidgee Valley, which is currently 2,052,455 megalitres (Table 1).

In determining the irrigation development/supply reliability scenarios a number of assumptions have been made. Foremost among these is that any further development in the Murrumbidgee Valley will occur along the river rather than in the irrigation areas and districts. This is due to a lack of suitable land that can be developed for irrigation by gravity flow at reasonable cost, and limitations on existing supply and drainage systems in the irrigation areas and districts. Development along the river by private diverters will be at private rather than public capital costs and there are few limitations on suitable land and water supply capacity as these irrigators pump their requirements directly from the river.

In addition to the assumption that all new irrigation development occurs along the river, it is also considered that this development will occur in the western portion of the valley, i.e. from Narrandera to the Murray River. This is because it is in this area that most of the land suitable for flood irrigation lies. The additional irrigation development is equally divided between zones 2 and 3.

Another assumption is that new licensed allocations to private diverters will be made on the basis that licensed areas will be determined at the rate of 6 megalitres per hectare. The study also assumes that "sleeper licenses"[3] will be activated so that all licensed allocations will be utilised.

The development scenario of 92 percent usage of licensed allocations represents the current base situation where usage is below licensed allocation. This is

---

2. Irrigation development is used to describe the level of allocation and licensed irrigation area.

3. The term sleeper licenses is used to describe licensed allocations which are held by individual landholders but which are rarely, if ever, utilised.

primarily due to the existence of the sleeper licences. To calculate this scenario it is assumed that all sleeper licences occur along the river, thus licensed allocation values in the private diverters model are reduced to a level which results in a 92 per cent usage for the entire Murrumbidgee Valley. This assumptions closely parallels reality.

Efforts are being made by the DWR to activate sleeper licenses through the introduction of permanent transferable water entitlements, changing water pricing structures, or the resumption of allocations.

The licensed allocations and areas for each of the development scenarios are presented in Table 2.

Table 1: **Current licensed allocations in the Murrumbidgee Valley (ML)**

	Allocation
Murrumbidgee Irrigation Area	660,945
Murrumbidgee Irrigation Districts	344,802
Coleambally Irrigation Area	446,700
Private diverters	600,008
Total Murrumbidgee Valley	2,052,455

Table 2: **Licensed allocations and areas for the increased irrigation development scenarios**

Level of Development (%)	Murrumbidgee Valley allocation (ML)	Private Diverters allocation (ML)	Private Diverters licensed area (ha)
Base	1,888,259	345,812	140,784
100	2,052,455	600,008	140,784
105	2,155,078	702,631	157,888
110	2,257,701	805,254	174,992
115	2,360,323	907,876	192,095
120	2,462,946	1,010,499	209,199
125	2,565,569	1,113,122	226,303
130	2,668,192	1,215,745	243,407
135	2,770,814	1,318,367	260,511
140	2,873,437	1,420,990	277,614
145	2,976,060	1,523,613	294,718
150	3,078,683	1,626,236	311,822

6. Results

6.1 Supply reliability levels

The supply reliabilities calculated by the hydrology simulation model for each of the irrigation development scenarios are presented in Table 3. Supply reliability is used to describe the percentage of years that irrigators receive their full allocation entitlement. This indicates that at the current level of irrigation development irrigators receive their entitlement 96 years in every 100. In most of these 96 years, irrigators would receive up to 120 per cent of their normal entitlement. As irrigation development is increased the level of supply reliability in the Murrumbidgee Valley declines. For example, at 130 per cent irrigation development, reliability is 68 per cent, and at 150 per cent development reliability is 57 per cent.

Reliability does not describe the severity of the water shortages that may occur. The irrigation development scenarios of 145 and 150 per cent have the same reliability of 57 per cent. This does not mean these development levels give the

same net income. It means that these scenarios result in the same number of years that normal entitlement at least is received, it does not describe the magnitude of the annual allocations. These will generally be lower for the larger development level. Figures 3 to 6 are presented to illustrate the increasing variability in annual allocations as irrigation development is expanded within the Murrumbidgee Valley. These figures show the annual allocation levels for the period 1891 to 1990 for four of the development scenarios studied.

The above discussion demonstrates the need to consider the level of allocation along with supply reliability in any study such as the one being conducted. Different allocation levels can have a similar supply reliability but vastly differing net income values.

Table 3: **Supply reliabilities at different development levels**

Level of development (%)	Supply reliability (%)
Base	96
100	91
105	87
110	84
115	80
120	78
125	73
130	68
135	67
140	62
145	57
150	57

Figure 5: Annual announced allocations at 92% development

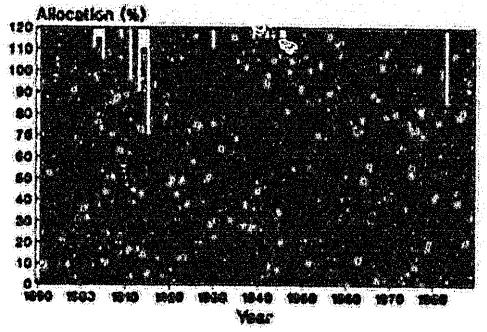


Figure 6: Annual announced allocations at 116% development

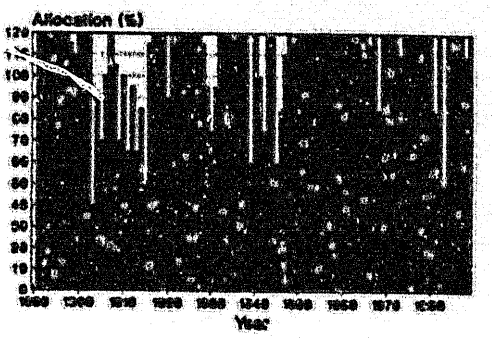


Figure 7: Annual announced allocations at 130% development

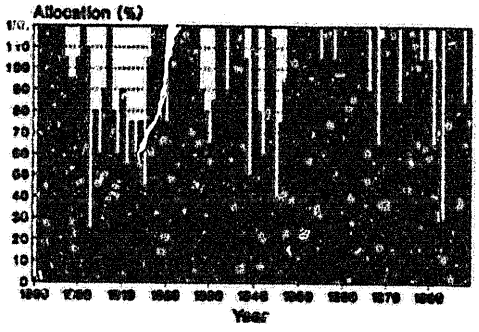
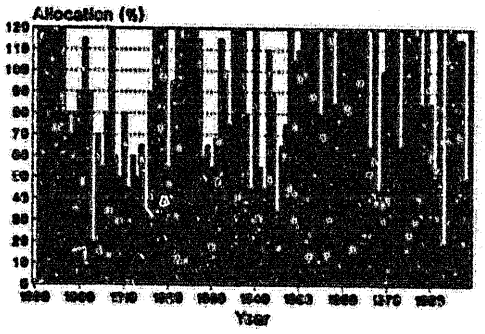


Figure 8: Annual announced allocations at 160% development



6.2 Regional net income level and optimal allocation and supply reliability

The average annual net income and standard deviations for the total Murrumbidgee Valley and the four separate regions are presented in Tables 4 to 8. These illustrate that, although there is an increase in regional income with increased irrigation development for the total Murrumbidgee Valley and the private diverters region, there are significant declines in net incomes for the MIA, MID, and CIA.

The null hypothesis tested is that the current supply reliability and allocation policy is optimal. The results in Table 4 illustrate that for each irrigation development scenario greater than the base allocation level, a greater average annual net income can be achieved. Therefore, the null hypothesis is rejected.

The results of the study for the total Murrumbidgee Valley is graphically presented in Figures 7 and 8, which plots the average annual net income against the irrigation development levels. The shape of this curve is consistent with Dudley's annual net revenue curve in Figure 1. The optimal level of allocation and supply reliability is deemed to be the point that has the highest net income value. This occurs at an irrigation development of 115 per cent and supply reliability of 80 per cent with the average annual net income being $100.6m. There is little difference in the average annual net income values for irrigation developments between 110 to 125 per cent, however the standard deviations for annual net income increase over this range. By moving to an irrigation development of 115 per cent from the base level, average annual net returns Murrumbidgee Valley could be increased by approximately $10m, or 10 per cent. However, there will be substantial distributive impacts from such a policy.

Any increases in irrigation development which leads to a reduction in supply reliability will result in declines in net returns in the MIA, MID and CIA. At an irrigation development level of 115 per cent, average net income in the MIA falls from $18.6m to $16.9m, representing a 9 per cent decline. Net returns in the MID are also reduced by 9 per cent for the same irrigation development, from $8.4m to $7.7m. There is a 23 per cent decline in average annual net income in the CIA, from $2.7m to $2.1m. Although the magnitude of the values for the CIA are not large in comparison to the Murrumbidgee Valley total, the impact upon individual irrigators may be substantial.

Offsetting the declines in net returns in these areas is an 18 per cent improvement in average annual net income for private diverters, from $71.0m at the base level to $83.4m at 115 per cent development. Average net returns continue to increase up to 140 per cent irrigation development (62 per cent supply reliability) when annual net income is $85.8m. After this point, the variability in annual returns becomes so great as to result in a decline in average annual net income.

Table 4: Average annual net income and standard deviation of the Murrumbidgee Valley

Level of development (%)	Annual net income ($m)	Annual standard deviation ($m)
Base	100.73	5.08
100	107.70	7.62
105	109.70	8.76
110	110.44	10.00
115	110.55	11.90
120	110.41	14.49
125	110.24	15.97
130	109.75	18.12
135	109.23	20.08
140	108.47	21.77
145	107.35	23.83
150	106.41	25.78

Table 5: Average annual net income and standard deviation of the Murrumbidgee Irrigation Area

Level of development (%)	Annual net income ($m)	Annual standard deviation ($m)
Base	18.57	1.44
100	18.04	2.34
105	17.71	2.87
110	17.37	3.39
115	16.91	3.92
120	16.48	4.42
125	16.03	4.72
130	15.57	5.05
135	15.15	5.37
140	14.72	5.66
145	14.29	5.95
150	13.91	6.17

Table 6: **Average annual net income and standard deviation of the Murrumbidgee Irrigation Districts**

Level of development (%)	Annual net income ($m)	Annual standard deviation ($m)
Base	8.42	0.63
100	8.19	1.03
105	8.04	1.28
110	7.88	1.53
115	7.68	1.77
120	7.49	2.00
125	7.29	2.13
130	7.08	2.29
135	6.89	2.44
140	6.69	2.58
145	6.48	2.72
150	6.31	2.82

Table 7: **Average annual net income and standard deviation of Coleambally Irrigation Area**

Level of development (%)	Annual net income ($m)	Annual standard deviation ($m)
Base	2.73	0.55
100	2.52	0.90
105	2.40	1.09
110	2.27	1.29
115	2.10	1.48
120	1.93	1.66
125	1.76	1.77
130	1.59	1.90
135	1.43	2.03
140	1.27	2.14
145	1.11	2.25
150	0.97	2.33

Table 8: Average annual net income and standard deviation of private diverters

Level of development (%)	Annual net income ($m)	Annual standard deviation ($m)
92	71.02	2.45
100	78.95	3.38
105	81.55	3.56
110	82.91	3.88
115	83.85	4.89
120	84.52	6.64
125	85.16	7.53
130	85.52	9.07
135	85.76	10.41
140	85.78	11.50
145	85.47	13.01
150	85.22	14.55

Figure 7: Average annual net income for the Murrumbidgee Valley

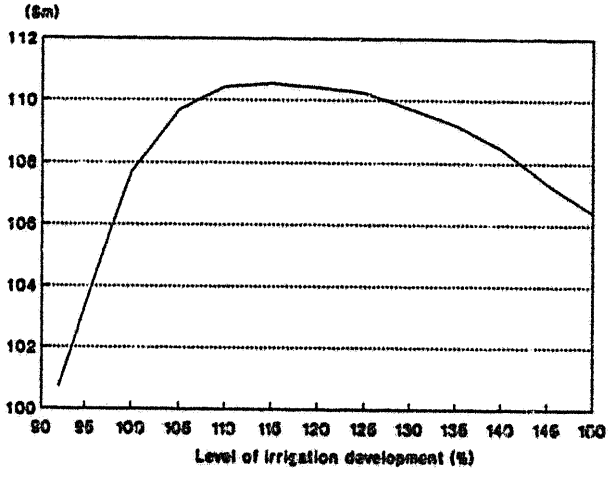
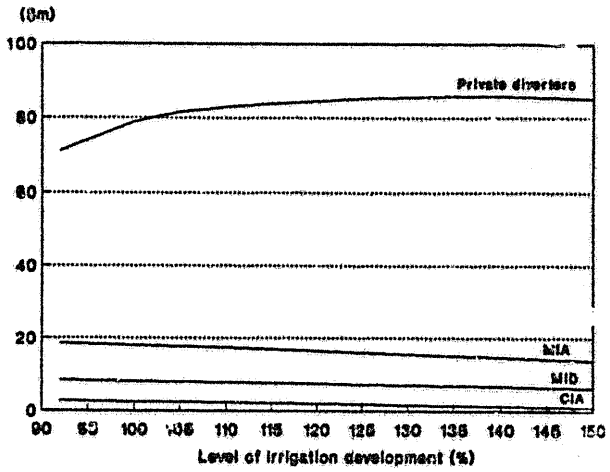


Figure 8: Average annual net incomes for the MIA, MID, CIA and private diverters



7. Summary and conclusions

The objective of this study has been to determine the optimal level of supply reliability and irrigation water allocation in the Murrumbidgee Valley. This has involved comparing the trade-offs involved with systems of differing reliabilities, those that attempt to maximise net revenue but also incur high income variance to those systems which aim to minimise income variance but have lower annual net returns on average. The framework presented by Dudley (1975) was used in this study, with the optimal allocation and reliability of supply being deemed to be the one that maximises average annual net income.

A combination of hydrology simulation and regional linear programming was used to determine the optimal level of supply reliability and allocation. The objective function used was the maximisation of regional net farm income, which was illustrated to be equivalent to net social benefit. A range of irrigation development scenarios were tested, from the base level (92 per cent usage of current licensed allocation) to 150 per cent development.

The null hypothesis, that the current level of allocation and supply reliability is optimal, was rejected. All the alternative irrigation development scenarios tested exhibited higher average annual net incomes, and corresponding standard

deviations, than the base level. The optimal irrigation development level was determined to be 115 per cent, which resulted in a 10 per cent increase in average annual net income to the base level. This irrigation development scenario has a corresponding supply reliability of 80 per cent. Any action taken by the Department of Water Resources to activate sleeper licenses and increase allocations along the Murrumbidgee River to within the level of this development will be an improvement in economic efficiency.

There will be distribution impacts associated with the introduction of any policy which leads to an optimal level of allocation and reliability. Although there is an overall increase in net returns at a 115 per cent irrigation development scenario, there are significant losses of average annual net income in the MIA, MID, and CIA. This would result in significant structural adjustment being required in these areas which are already experiencing the impact of depressed commodity prices and detrimental effects of land degradation through soil salinisation and waterlogging.

The introduction of demand management measures, particularly permanent water transferability, is seen as critical to the success of an optimal supply reliability and allocation policy as an agent of reform. This further supports the need for packages of reform rather than isolated ad hoc components. Transferable water entitlements would allow those irrigators who are adversely affected by a reduction in supply reliability the ability to obtain additional water via a market. They would then be able to determine as individuals the reliability of supply they require. This will be a commercial decision, and may differ among individual irrigators depending on their farm structures, managerial ability and risk preferences.

References

Arch, A.M.J., and Penman, P.F. (1983), Implications for the rice industry of the introduction of volumetric water allocations in the MIA, Paper presented at the Twenty-seventh Annual Conference of the Australian Agricultural Economics Society, Brisbane, February.

Bootle, B.W. (1988), Trade-offs in the determination of supply reliability and the extent of development of irrigation on the unregulated Barwon-Darling River, Paper presented at the Thirty-second Annual Conference of the Australian Agricultural Economics Society preliminary workshop on resource economics, Melbourne, February.

Briggs Clark, J., Menz, K., Collins, D., and Firth, R. (1986), A model for determining the short term demand for irrigation water, BAE Discussion Paper 86.4, AGPS, Canberra.

Centre for Water Policy Research (1989), A study of reliability of water supply for irrigated cotton in the Namoi Valley, University of New England, Armidale.

Davidson, B.R. (1969), Australia Wet or Dry? The Physical and Economic Limits to the Expansion of Irrigation, Melbourne University Press, Melbourne.

Dent, J.B., Harrison, S.R., and Woodford, K.B. (1986), Farm Planning with Linear Programming: Concept and Practice, Butterworths, Sydney.

Dudley, N. (1975), Trade-offs between irrigation systems with different reliabilities of supply, Paper presented at a technical conference of the Institution of Engineers, Australia.

Flinn, J.C. (1969), 'The demand for irrigation water in an intensive irrigation area', Australian Journal of Agricultural Economics 13(2), 128-43.

Hardaker, J.B. (1971), Farm Planning by Computer, Technical Bulletin 19, Ministry of Agriculture, Fisheries and Food, London.

Hashimoto, T., Stedlinger, J.R. and Loucks, D.P. (1988), 'Reliability, resiliency, and vulnerability criteria for water resource system performance evaluation', Water Resources Research 18(1), 14-20.

_____, Loucks, D.P. and Stedlinger, J.R. (1988), 'Robustness of water resources systems', Water Resources Research 18(1), 21-26.

Howe, C.W. (1985), 'Economic, legal, and hydrologic dimensions of potential interstate water markets', American Journal of Agricultural Economics 1226-30.

_____ (1990), 'An analytical framework for water transfers'. In J.J. Pigram and B.P. Hooper (ed.), Transferability of Water Entitlements, Proceedings of an international seminar and workshop, University of New England, Armidale, 4th-6th July.

Irrigation Farm Working Group (1986), The Profitability of Large Area Irrigation Farms in the Murrumbidgee and Murray Valleys of NSW, Report to the NSW Minister for Agriculture, Lands and Forests, December.

Murrumbidgee Irrigation Areas and Districts Management Board (1990), Water Pricing for the Murrumbidgee Region Irrigation Areas and Districts, Presented to the Chief Secretary and Minister for Water Resources, December.

Musgrave, W.F. (1972), 'The political economy of resource use: Water'. In J.A. Sinden (ed.) The Natural Resources of Australia: Prospects and Problems for Development, Angus and Robertson, Sydney.

_____, Alaouze, C.M. and Dudley, N.J. (1988), 'Capacity sharing and its implications for system reliability'. In G.C. Dandy and A.R. Simpson (ed.) Proceedings of the National Workshop on Planning and Management of Water Resource Systems: Risk and Reliability, AGPS, Canberra.

Randall, A. (1981), 'Property entitlements and pricing policies for a maturing water economy', Australian Journal of Agricultural Economics 25(3), 195-220.

_____, (1982), 'Resource allocations in a maturing economy'. In Australian Rural Adjustment Unit, Irrigation Water: Policies for its Allocation in Australia, University of New England, Armidale.

Reynolds, R.G., Watson, W.D. and Collins, D.J. (1983), 'Water resources aspects of drought in Australia', Water 2000: Consultants Report No. 13, Department of Resources and Energy, AGPS.

Rickards, P.A. and Passmore, A.L. (1977), Planning for Profit in Livestock Grazing Systems, Professional Farm Management Guidebook number 7, Agricultural Business Research Institute, Armidale.

Ryan, J.G. (1969a), 'Optimum programmes for irrigated farms', Review of Marketing and Economics 37, 153-71.

_____ (1969b), Input-output Data, Resource Restrictions and a Programming Matrix for Rice Farms on the Murrumbidgee Irrigation Area, Miscellaneous Bulletin 9, NSW Department of Agriculture, Sydney.

Verdich, P. and Bryant, M. (1985), 'Optimal reliability of irrigation water supply - a management tool for water planners', Planning and Management of Water for Agriculture in the Tropics-institional Arrangements, Paper presented at the Fifth Afro-Asian Regional Conference of the International Commission on Irrigation and Drainage, Townsville, Australia.

Warford, J.J. (1968), 'Water supply'. In R. Turvey (ed.) Public Enterprise, Penguin Modern Economic Readings, Harmondsworth.

Watson, W.D., (1984), Perspective on water resources toward the year 2000, Paper presented at the Twenty-eighth Annual Conference of the Australian Agricultural Economics Society, Sydney, February.

_____ and Rose, R.N. (1980), Irrigation issues of the eighties: Focusing on efficiency and equity in the management of agricultural water supplies, Paper presented at the Twenty-fourth Annual Conference of the Australian Agricultural Economics Society, Adelaide, February.

_____, Reynolds, R.G., Collins, D.J. and Hunter, R.D. (1982), 'Agricultural water demand and issues', Water 2000: Consultants Report No. 5, AGPS, Canberra.

_____, Dudley, N. and Clarke, J. (1985), Water reliability policies in Australian irrigated agriculture, Research project final report, Australian Water Research and Advisory Council, Department of Primary Industries and Energy, Canberra.

Young, R.A. and Haveman, R.H. (1985), 'Economics of water resources: A survey'. In A.V. Kneese and J.L. Sweeney (ed.), Handbook of Natural Resource and Energy Economics Volume II, North-Holland, Amsterdam.