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The value of inter seasonal arbitrage in water markets

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There is pressure in Australia for water management reform to ensure an efficient allocation of resources between productive uses and to provide adequate conservation of the environment. The establishment of water markets and trade has been seen as the primary mechanism for improving the efficiency of water use in the Southern Murray Darling Basin. However, with the existing trading arrangements, irrigators can only reallocate water within a season. Individuals do not hold property rights that allow them to manage the variability in water demand and supply between seasons. The objective of the study presented in this paper is to establish an order of magnitude for the benefits of property rights that allow for inter-seasonal arbitrage in water markets.

A stochastic optimal control model was developed for the Murrumbidgee catchment, which integrates agronomic, economic and hydrologic aspects of farm irrigation. The modelling framework allows consideration of the impact of alternative strategies for the pricing of water released from storages, when there exists uncertainty in both water availability and demand. The current allocation system adopted in the Murrumbidgee valley has the traded price of water largely determined at the start of the irrigation season according to allocation levels. The impact of this strategy on water use and farm incomes is compared with that which would arise from a system of property rights that allow trade of water held in storage within and between seasons.

The results indicate that under a system of storage access rights which allows trade between seasons, irrigators could increase returns compared to the current allocation rule by reducing the average amount of water held in storage between seasons. The increase in returns was estimated to be in the order of $700 million, discounted over 30 years. However, the associated increase in water use would result in lower but more volatile water prices and greater variability in water use between seasons. Realising these benefits might require investments in delivery and farm infrastructure. There would also be implications for the overall management of water flows for the environment.

ABARE Project 1568

1. Introduction

The focus for water management reforms in Australia has been directed at determining measures that will ensure an efficient allocation of resources between productive uses and provide adequate conservation of the environment. In the Southern Murray Darling Basin, the establishment of water markets and trade has been seen as the primary mechanism for improving the efficiency of water use. However, with the existing administrative system of determining annual allocations, trade can only improve the allocation of water within a season. Individuals do not hold property rights that allow them to manage the variability in water demand and supply between seasons.

Trade in water allocated on this basis would generate an efficient allocation between irrigators provided that neither storage nor distribution capacity limits the availability of water. The introduction of access rights to water delivery infrastructure in the peak irrigation season has been shown to potentially improve the efficiency of water use within a season when there is trade in water entitlements (see Beare and Bell 1998). To enable irrigators to manage variability between seasons, a system of property rights that allows trade of water held in storage would be necessary. The potential value of moving to such a system of property rights is the focus of the research reported in this paper.

A stochastic optimal control model, which integrates agronomic, economic and hydrologic aspects of farm irrigation, is developed for the Murrumbidgee catchment. The modelling framework allows consideration of the impact of alternative strategies for the pricing of water released from storages, when there exists uncertainty in both water availability and demand.

The current allocation system adopted in the Murrumbidgee valley has the price of water largely determined at the start of the irrigation season according to allocation levels. The impact of this strategy on water use and farm incomes is compared with that which would arise from a system of property rights that allow trade of water held in storage within and between seasons. It would be expected that rigidity associated with an annual allocation system would result in both lower farm incomes and lower total economic return to the use of water, relative to that which could be achieved under a more flexible market regime. These potential benefits must be weighed against the transactions costs of establishing and administrating an expanded property rights scheme that includes infrastructure access rights.

2. Water availability and use in the Murrumbidgee Valley

The Murrumbidgee River is a major tributary of the Murray River, with two principal storages that supply irrigators upstream of the confluence to the Murray. The Murrumbidgee Valley operates largely in isolation from the remainder of the river system in the southern Murray Darling Basin, although it is a supplier to demands outside the catchment. It is for this reason that the Murrumbidgee Valley was chosen as a case study for the analysis. A schematic diagram of the Murrumbidgee system is shown below.

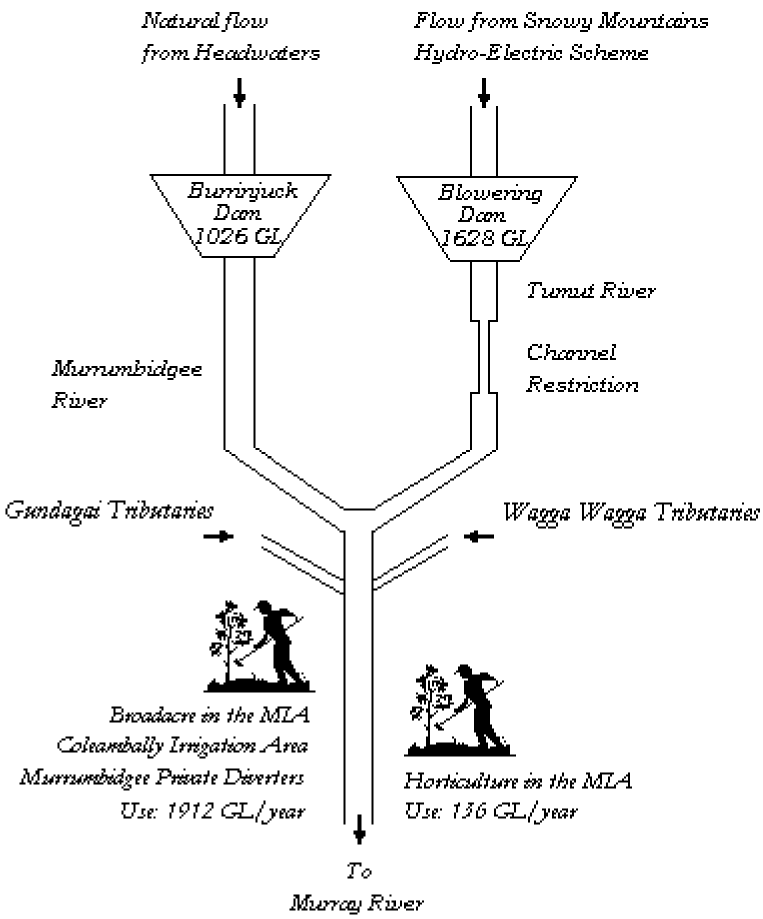
2.1 Water storage in the Murrumbidgee Valley

Storage capacity tends to constrain the system in years in which there is high winter and spring inflows and when storages are nearly full at the end of the previous irrigation season. The value of additional inflows is limited by the extent to which storage capacity becomes a constraining factor.

However, the likelihood that storages will reach capacity depends on administratively determined allocations and water management practices. Lower allocations and the maintenance of storages, such as Burrinjuck, at near full capacity increases the security of the system. At the same time, such a strategy increases the likelihood of forced spills. Higher allocations may reduce the likelihood of losing water through forced spills from the storages, while at the same time reducing the security of future allocations.

As individual irrigators currently cannot trade in access to storage capacity, trade may not lead to an efficient allocation of water between seasons. The management of the risks and returns to alternative storage strategies rests with the administrative authority.

Figure 1: The Murrumbidgee irrigation system

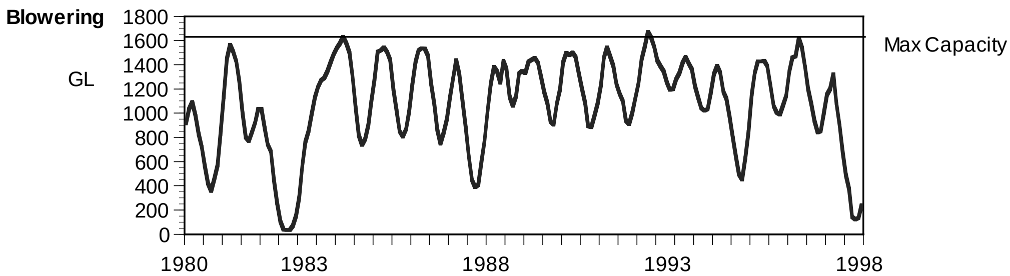


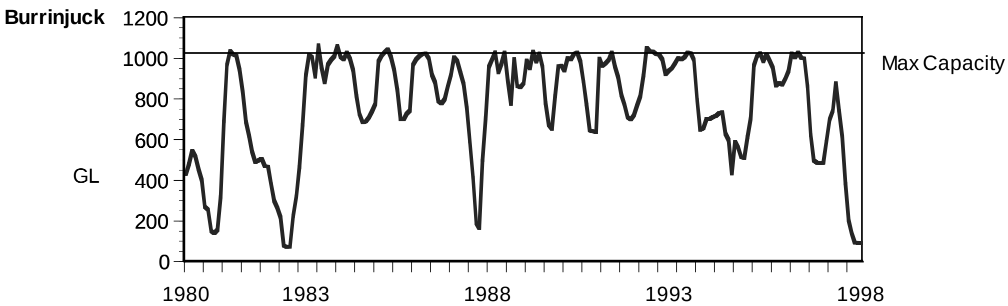
Storage levels at Blowering and Burrinjuck dams are shown in figure 2. Inflows into Blowering storage are relatively reliable as it receives controlled releases from the Snowy Mountains Hydro-Electric Scheme. As a result, forced spills owing to capacity constraints have occurred in only two of the past eighteen years at Blowering dam.

In contrast, Burrinjuck dam has highly variable inflows in winter and early spring, with negligible inflows during the peak irrigation season. Forced spills have occurred in most years at Burrinjuck.

This divergence in the pattern of forced spills for the two storages reflects the way in which the storages are operated, with priority given to meeting irrigation demands with releases from Blowering. In part, this reflects the fact that because of channel restrictions, simultaneous releases from both storages are required to meet peak season irrigation demand. Given the characteristics of the two storages, the system tends to become constrained by the availability of water in Burrinjuck dam. Hence, Burrinjuck is operated to ensure that peak season irrigation requirements are met. However, forced spills are allowed to occur more frequently.

Figure 2: Historical volume of water held in Blowering and Burrinjuck storages





In general, it is the marginal water users who are most affected by variations in the availability of water within and between seasons. In most years, water is available to, or withdrawn from, the relatively low valued uses such as the irrigation of annual pastures. In successive drought years, reduced water availability may restrict the amount of water available to produce higher valued crops such as rice.

2.2 Irrigation in the Murrumbidgee Valley

Irrigated agriculture along the Murrumbidgee consists largely of two types of farm enterprises: mixed cropping and livestock production, and horticulture. Mixed cropping and livestock production accounts for about 83 per cent of water use in the region, with rice, wheat and canola being the major irrigated crops and irrigated pasture being used for the raising of sheep and beef cattle.

Horticultural production accounts for nearly 10 per cent of water use (Murrumbidgee Irrigation 1997). The principal horticultural crops are citrus and grapes. Irrigation demands are highly seasonal, with the irrigation peak from December to February each year, no irrigation in June and July, and little to no irrigation in August.

Irrigators in the Murrumbidgee Valley receive an annual allocation for water, based on the quantity of water in storage and expected inflows. At the start of the irrigation season, irrigators are allocated water based on a share of the storage volumes plus a conservative estimate of future inflows for the season. Allocations are adjusted throughout the season taking into account both actual inflows and use.

Samaranayaka, Freeman and Short (1998) reported that, on average, horticultural irrigators in the Murrumbidgee Irrigation Area used only 62 per cent of their annual allocation in the 1996-97 irrigation season, while broadacre irrigators used around 89 per cent of their annual allocation. This would suggest that the Blowering and Burrinjuck storages are not fully used. However, variability in historical dam volumes suggests that there is not a consistent pattern of underuse of entitlements. Further, these allocations do not include losses incurred during conveyance between the storage and farms.

Conveyance losses include seepage and evaporation, as well as losses associated with maintaining channel flows to allow extraction on demand and orders in excess of requirements. In determining storage releases for irrigation in the Murrumbidgee Valley, the New South Wales Department of Land and Water Conservation assumes around 70 gigalitres a year (3 per cent of total releases) is lost to evaporation and around 520 gigalitres (25 per cent of total releases) to conveyance losses between storages and irrigation regions (Snowy Water Inquiry 1998). Further losses incurred in conveyance of water from irrigation channels to the point of application on farms have been estimated to be around 20 to 25 per cent (Hall, Poulter and Curtotti 1994).

2.3 Trade and administrative arrangements

Total water use in the Murray Darling Basin is capped each year in order to contain diversions from rivers at predetermined levels. The cap is aimed at not only protecting the quality of the river environment, but also protecting downstream users from increased water extractions upstream (Department of Land and Water Conservation 1998b). The actual cap varies from year to year with seasonal conditions. In the Murrumbidgee Valley the cap has been around 100 to 120 per cent of the annual base level allocation of 2120 gigalitres in recent years. The NSW Department of Land and Water Conservation modifies access to on and off allocation water to maintain diversions within cap levels (Department of Land and Water Conservation 1998b).

Arrangements are in place in the Murrumbidgee Valley which allow both permanent and temporary (within a season) trade in water. While there has been a considerable expansion of trade in annual allocations in recent years (Department of Land and Water Conservation 1998a), trade in permanent water entitlements has remained low, in part, because of uncertainty about seasonal conditions and the policy environment. In 1998, trading was extended in NSW to allow industrial or mining water users to purchase additional water rights without needing to acquire an irrigation property (Department of Land and Water Conservation 1998a). In addition, trade between catchments is permitted where there is a common source or outlet, such as in the Murrumbidgee and Murray Rivers. Nevertheless, preliminary investigations of the effectiveness of water trading operations in NSW conclude that while trading offers substantial benefits to individual water users, it is currently operating less than optimally (Department of Land and Water Conservation 1998a).

To encourage more efficient water use, the NSW government began in October 1998 to trial water carry-over schemes in the Namoi and Gwydir valleys in the north of the state and is proposing that capacity sharing schemes be introduced more widely (Department of Land and Water Conservation 1998b). Under the trial scheme, water users are permitted to take unused allocation from the end of one season and use it in the next. Accounts are limited to 150 per cent of licensed entitlements. Use in any given season is restricted to no more than 100 per cent of the entitlement, although additional water can be purchased through temporary trade. The benefits of moving toward a capacity sharing approach is the focus of this paper.

3. Modeling water availability and demand

3.1 Background to the capacity sharing approach

The benefits of introducing a system of property rights that would enable irrigators to trade entitlements to water held in storage have been purported in earlier work (for example, Dudley 1988, and Dudley and Musgrave 1988). Capacity sharing involves allocating shares of inflow, storage capacity and losses among users of water and allowing these users to operate their shares to meet their own individual objectives. Dudley and Musgrave (1988) note that the components of the capacity sharing arrangement could be tradeable, but they do not investigate this aspect further.

Building on the work of Dudley and Musgrave (1988), Alaouze (1991) develops a stochastic dynamic programming model for a single storage with two users of water and a single demand season for each year. Surplus water is not accumulated between irrigation years and trade in water entitlements and allocations is not considered. Alaouze demonstrates that the value of expected profits under storage capacity sharing may be at least as high as under release sharing, an approach similar to that currently used in the southern Murray Darling Basin.

What has not been assessed to date, and what this paper attempts to address, is the potential value of moving from the current allocation system to a system in which irrigators are able to trade in these property rights.

3.2 Interseasonal trade

Under the current allocation system in the southern Murray Darling Basin, the water associated with any unused allocation at the end of the irrigation season is either made available as off-allocation water to all irrigators or retained in storage for the following season. That is, unless irrigators trade unused allocations, property rights to any unused allocations for that irrigation season are effectively forfeited. Under a capacity sharing system, property rights to each component of the water resource may be clearly specified in the sharing arrangement, enabling irrigators to trade their entitlement over irrigation seasons.

Enabling water users to trade their entitlement to water between irrigation seasons provides irrigators and other water users with greater incentive to efficiently use water, as any water savings achieved by water users in one year would be available for use or trade by them in later years. An irrigator would hold over his allocation of water in storage to a later year if he expected to be able to achieve a greater return on that water in a later year, either through its use or trade. The future availability of, and demand for, water then determine the value of the water held in storage.

3.3 A model for the current and an optimal system of water releases

3.3.1 Model design

An assessment of the optimal value of irrigation water under supply and demand uncertainty and infrastructure constraints is based on the stochastic optimal control framework and simulation model developed in Beare, Bell and Fisher (1998). Within the approach, both inflows into the system and water demands are subject to random variation. Specifically, expected water demand is derived for a number of farms with a capacity share in stored water, and with irrigation demand subject to uncertainty due to seasonal variability. Uncertainty in water availability arises due to seasonal variability that affects storage inflows, and losses to evaporation and seepage. Constraints on infrastructure are added to the framework by introducing capacity limits on storage volumes and release rates. The objective of the optimisation is to develop a pricing rule for water held in storage, that maximises the total economic benefit of water use.

The simulation model was coded in Extend (Imagine That Inc. 1997) and consists of four object modules that embed a number of individual routines. The optimisation and dam management routines are contained in a high level module which also controls the execution of the simulation. Storage inflow data are generated in a seasonal module while storage modules are used to determine volumes and maximum outflows, given the physical characteristics of Blowering and Burrinjuck dams. Farm level modules are used to specify the demand for irrigation water and the net farm returns.

Stochastic data for storage inflows were generated from monthly historical rainfall data for the southern Murray Darling Basin using the procedure described in Appendix A. The amount of water available for distribution was then adjusted for evaporative losses using daily evaporation pan data for Blowering and Burrinjuck storages. Irrigation demands by broadacre and horticultural farm enterprises were calibrated as in Appendix A, using price elasticities of annual demand for water and historical monthly irrigation diversion data for the Murrumbidgee Irrigation Area.

3.3.2 Simulation design

The principal focus of the simulations was to evaluate the benefits of moving from the current allocation system to one in which irrigators are able to manage water variability between seasons. The impact on these potential benefits of uncertainty in water supply and irrigation demands was then assessed.

Two sets of simulations were undertaken to evaluate the benefits of managing water variability between seasons. In the first set, the current allocation system was simulated with the impact of uncertainty in water supply and irrigation demands assessed through a comparison of a deterministic with a stochastic simulation. To replicate the current system of determining storage releases in the Murrumbidgee Valley, the modelling procedure adopted by the NSW Department of Land and Water Conservation to estimate the total annual allocation at the start of the irrigation season was utilised (see appendix A.4).

It was assumed that water prices are related to seasonal demands and the remaining quantity of water that has been allocated (see appendix A.5). Pricing rules are determined as a periodic function of time and the remaining allocation such that aggregate net revenue in the current irrigation year is maximised. That is, a pricing rule is determined for each irrigation season reflecting the fact that irrigators do not take into account the impact of their current year allocation and use strategies on water availability in later years. Temporary trade in water within an irrigation season can occur, but there is no temporary trade in water between seasons.

In the second set of simulations, an optimal pricing rule, which allows both within season and between season trade in water, was evaluated in both a deterministic and stochastic simulation. A single pricing rule is derived which varies with the current state of the system, taking account of both the time of year and the total water available in storage (see appendix A.5). It was assumed that water prices are chosen to maximise the net present value of accumulated revenue over a 30 year planning horizon. Temporary trade in water can occur both within and between irrigation seasons. Unlike the trial undertaken in the Namoi and Gwydir valleys of NSW, no restriction has been made here on either the quantity of water which can be carried over between seasons, or the proportion of water available which can be used each year.

4. Evaluating the benefits of water trade

The results from the two sets of simulations are detailed in Table 1. The principal difference between the current allocation system with intra-seasonal trade and the optimal pattern of water use, is the additional water use that occurs when inter-seasonal trade is allowed. That is, under the model assumptions, the allocation system operates at a higher level of security and with lower returns than would occur if there were tradeable rights to storage infrastructure.

In the deterministic simulations seasonal conditions are identical in each year hence there are no benefits to transferring water between seasons. Restricting the total allocation to not exceed 120 per cent of the annual base level allocation simply reduces water availability, resulting in higher water prices and lower economic returns when compared with the optimal pattern of water use.

Table 1: Simulation results

	Deterministic		Stochastic			
	Allocation System	Optimal Pricing Rule	Allocation System		Optimal Pricing Rule	
			Mean	Stdev	Mean	Stdev
Water price[a] ($/ML)	29.86	8.41	30.12	15.71	16.80	16.37
Water demanded (GL)	1800	2442	1753	433	2152	567
Revenue ($m NPV)						
Broadacre	7,604	8,895	7,518		8,329	
Horticulture	3,597	3,686	3,575		3,640	
Water Sales	432	137	423		228	
Aggregate	11,633	12,718	11,516		12,197	

a expected price of water in storage

In the stochastic simulations, seasonal conditions vary between years and there are potential benefits from transferring water use across seasons. The restriction on diversions under the current allocation system effectively transfers water from a high inflow year to the following year. Furthermore, the use of conservative estimates of expected inflows to determine allocations at the start of the irrigation season shifts water use to toward the end of the irrigation season (figure 3). The water use patterns reflect the different pricing rules for water in storage (figure 4). Under the optimal pricing rule, less water is transferred between seasons and more water is used earlier in the irrigation season, resulting in a higher overall level of water use and a higher economic return.

Figure 3: Expected quantity of water demanded

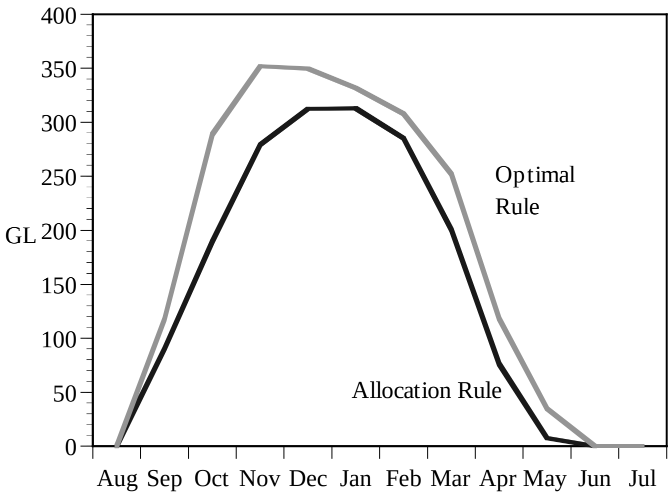
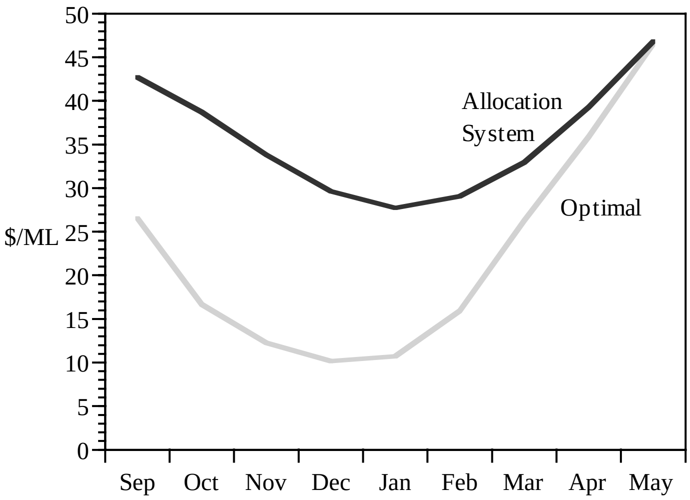


Figure 4: Rule price for water in storage

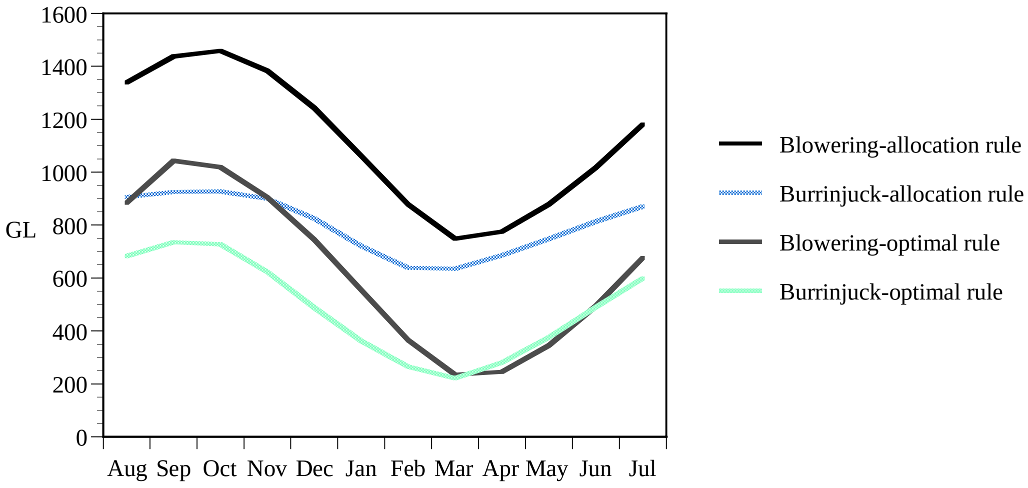


The optimal pricing rule results in a lower level of system security, with storage levels at Blowering averaging about 50 per cent lower at the end of the irrigation season when compared to the current allocation system (figure 5). The corresponding reduction at Burrinjuck was only 20 per cent, reflecting the role of Burrinjuck in meeting peak season irrigation requirements under the current allocation system.

Overall, the increase in economic returns associated with moving from the current allocation system to one allowing inter seasonal trade was almost $700 million, over 30 years. The average price of water was about 50 per cent lower and the average quantity of water demanded was over 20 per cent higher. However, there was greater variability in both traded water prices and water use under the optimal pricing rule.

To derive these additional benefits may require a shift in the timing of releases from Blowering and Burrinjuck storages. Specifically, a reduction in forced spills from the storages during winter and spring would be necessary, with more releases during the peak of the irrigation season. Such a change in the flow pattern is likely to have an impact on the environment and the cost of this should be assessed against the benefits derived from inter seasonal trade. Downstream industrial and commercial water users may also be affected by a change in the timing of flows.

Figure 5: Expected volume of water held in storage



5. Conclusions

Establishing tradeable access rights to storage infrastructure would allow water users to make market based decisions regarding the use and conservation of water between seasons. This could be achieved through a system of property rights that allowed irrigators to trade water held in storage, within and between seasons, in a competitive market. Irrigators would be able to trade-off the level of risks they face with the returns they can generate from water use.

In this study of the Murrumbidgee Valley, the results indicate that under an optimal system of storage access rights, irrigators could increase returns by reducing the average amount of water held in storage between seasons, when compared to the current allocation rule. This increase in returns was estimated to be in the order of $700 million over 30 years. The associated increase in water use would result in lower but more volatile traded water prices and greater variability in water use between seasons.

At present, these benefits of capacity sharing may not be realisable in the southern Murray Darling Basin, where given existing storage capacity and allocation rules, water security is relatively high. Further, restrictions on diversions in the Murrumbidgee Valley may mean that irrigators cannot increase water use on average, hence capacity sharing schemes could be of limited benefit. If irrigators are able to increase average use, with a consequent reduction in the security of the system, consideration would also have to be given to how changed storage operation may impact on other downstream water users and on the reliability of environmental flows. A shift in the timing of storage releases into the irrigation season is likely to have an impact on the environment and the cost of this should be assessed against the potential benefits derived from inter seasonal trade.

Appendix A: Model Calibration and Estimation

A.1 Inflow Model

Inflows into the Murrumbidgee storage and river system were estimated as monthly inflows into the Blowering and Burrinjuck storages and Murrumbidgee River inflows downstream of the two storages, from Gundagai and Wagga Wagga Tributaries. Data were obtained, for the period 1905 to 1991, from historical rainfall data for the southern MDB and information on the seasonal pattern of releases from the hydro-electric dams upstream of Blowering and Burrinjuck. The general statistical approach to modelling the inflows, accounting for both spatial and temporal correlations follows that of Gooday (1997). The statistical model was constructed in three stages.

In the first stage, the square root of the inflow was taken to reduce the skewness of the data and the principle components of the transformed flow data were extracted to remove the spatial correlation between the four series. Each component was then modelled using the following estimation equation

(A1) $$x_t = \delta_0 + \delta_1 \cos\left(\delta_2 + \frac{t\pi}{6}\right) + \delta_3 x_{t-1} + \varepsilon_t$$

Estimates were obtained using a non-linear estimation procedure in MATLAB (The Math Works Inc. 1997) and the results are summarised in Table 2. First differences in the actual versus predicted components were used to calculate R^2 values of 0.61 for the first component, 0.15 for the second component and 0.21 for the third and fourth components. Further analysis indicated that the residuals were kurtotic and exhibited a weak seasonal pattern.

Table 2: Inflow estimation results

	δ_0	δ_1	δ_2	δ_3	STD(ε)
1st Principle Component (Blowering)					
estimate	136.6	101.5	-49.8	0.7	147.6
10% CI	113.5	88.5	-49.9	0.7	141.5
90%CI	159.7	114.4	-49.6	0.8	154.3
2nd Principle Component (Burrinjuck)					
estimate	-38.3	-12.1	-38.7	0.4	89.8
10% CI	-44.9	-19.9	-39.3	0.3	86.0
90%CI	-31.8	-4.3	-38.0	0.4	93.8
3rd Principle Component (Gundagai Tributary)					
estimate	-84.7	28.4	27.5	0.4	62.6
10% CI	-93.7	22.8	27.3	0.4	60.0
90%CI	-75.6	34.1	27.7	0.5	65.4
4th Principle Component (Wagga Wagga Tributary)					
estimate	84.8	-21.0	-4.8	0.4	55.7
10% CI	75.7	-26.0	-5.0	0.4	53.4
90%CI	94.0	-16.1	-4.5	0.5	58.2

The stochastic generating function used for the simulation is given by the inverse transformation

(A2)
$$\tilde{x}_t = \left[\tilde{\delta}_0 + \tilde{\delta}_1 \cos\left(\tilde{\delta}_2 + \frac{t\pi}{6}\right) + \tilde{\delta}_3 (xPC)_{t-1}\right]^2$$
$$\tilde{\varepsilon}_t \sim N[\mu(\varepsilon), \sigma(\varepsilon)]$$

where PC is the transformation matrix of the principle components. Noting the comments regarding the residuals from the estimation equation, the statistically generated inflows will understate the extremes of the distribution of inflows and miss higher order temporal correlations in inflows.

A.2 Storage Management Model

A.2.1 Evaporation

Evaporation losses were determined from monthly net evaporation rates and estimated storage surface areas. Equations relating surface area (*SA* in hectares) to storage volumes *V* were obtained from the NSW Department of Land and Water Conservation

$$\text{(A3)}\qquad \begin{aligned} \mathrm{SA}_{\mathrm{Blowering}} &= 3.656 + 4.126V - 0.1079\left(\frac{V}{1000}\right)^2 \\ \mathrm{SA}_{\mathrm{Burrinjuck}} &= 648 + 4.76V \end{aligned}$$

Daily evaporation pan data for the two sites were obtained from the Department of Meteorology for the period 1970 to 1998 and are summarised in table 3. While it is reasonable to expect that inflows and evaporative losses would be negatively correlated over time, evaporation is only a small proportion of total system losses and this correlation was ignored.

Table 3: Net Evaporation Rates

	Blowering		Burrinjuck	
	Mean	Std Dev	Mean	Std Dev
	mm	mm	mm	mm
January	202.75	25.71	175.22	25.12
February	164.62	18.55	149.88	28.16
March	137.53	14.05	120.89	22.89
April	75.41	11.45	64.51	10.27
May	43.67	5.73	38.23	5.43
June	28.16	5.14	25.02	4.86
July	29.67	5.82	26.49	3.15
August	43.84	6.95	37.47	5.59
September	65.29	7.54	56.70	7.32
October	105.39	13.80	93.62	13.10
November	140.68	20.52	122.35	27.64
December	190.28	25.93	164.64	29.55

In simulation, initial values for storage volumes were required for both dams. These were set at the average opening volumes at the start of the irrigation year (August). In the allocation rule simulation, the storage volume was reset at the end of each irrigation year (end of May) to a level drawn randomly from the set of May volumes from the period 1961 to 1992.

A.2.2 Storage Releases

The distribution of required releases from the two storages to meet irrigation demands is determined in the model as a part of the genetic algorithm search. Targeted releases from each storage were determined from the following formula

(A4)
$$\text{Release}_i = Demand\left(\frac{\dfrac{weight_i V_i}{V_{i\max}}}{\displaystyle\sum_{i=1}^{2}\dfrac{weight_i V_i}{V_{i\max}}}\right)$$

where

$$weight_{Blowering} = 0.95$$

$$weight_{Burrinjuck} = 0.05$$

where V_i is the volume of water held in the i^{th} storage which has a maximum capacity of $V_{i,max}$. Targeted releases may be infeasible due to downstream channel constraints and are adjusted as required.

A.3 Water Allocation Model

In the simulation of water use under the current allocation system in the Murrumbidgee Valley, the procedure used by the NSW Department of Land and Water Conservation was utilised to determine the allocation each month. The allocation level is determined as follows:

(i) Expected inflows to Blowering and Burrinjuck storages and tributary inflows below the storages are estimated for the remainder of the irrigation year. These flows are a conservative estimate of inflows (drawn from historical estimates of the lowest 10^{th} percentile flows) that could be obtained and are adjusted for expected losses to evaporation and seepage. It is further assumed, conservatively, that dam managers receive 80 per cent of their minimum notification of annual releases from the Snowy Mountains Hydro-electric Scheme.

(ii) Total water available to be distributed to all uses are determined as the sum of current storage volumes, expected inflows, and an estimate of water available from the Snowy Mountains Hydroelectric scheme, including a return for Blowering airspace.

(iii) Water available for distribution to irrigators is estimated as total water available for distribution net of water retained to meet Murray Darling Basin commitments and reserve requirements or lost to seepage and evaporation.

(iv) The total allocation for irrigators each month is the sum of water available for distribution to irrigators and total releases in the irrigation year to date. The allocation is restricted to be no greater than 120 per cent of the total annual base allocation of 2120 gigalitres.

A.4 Irrigation Water Demand Model

The farm level models were calibrated using annual demand elasticities derived from previous studies and historical irrigation diversion data. Two farm types were calibrated: a broadacre farm producing livestock, summer and winter crops (including rice) and a horticultural farm producing citrus and grapes.

From Beare, Bell and Fisher (1998), the profit maximising rate of demand for water *w* is given by

$$\text{(A5)} \quad w(t) = \frac{1}{2\alpha_2(1-l)}\left\{\alpha_1 - \frac{c}{p(1-l)\left[\alpha_3 + \alpha_4\cos\left(\alpha_5 + \frac{t\pi}{6}\right)\right]} + 2\alpha_2\omega(t)\right\}$$

where t is time in months, p is the output price, c is the cost of water delivered on farm, l is a water transmission loss rate, and $\omega(t)$ is a stochastic process representing climatic uncertainty, with an expected increment value of zero and variance η_t^2. The α_i terms are positive parameters of the farms profit and production functions, as specified in Beare, Bell and Fisher (1998). The elasticity of water demand is assumed to be high during periods of low water use and low during periods of high water use.

The demand model parameters were determined using 30 years of monthly diversion data from the MIA and data on gross margins for water in Mues and Opalinska-Mania (1998). The diversion data series was not stationary so the data were transformed into a stationary series of monthly proportions of the annual demand for each year. Diversion data were not available by farm type hence an identical demand pattern was used for each farm type. The estimating equation is then

$$\text{(A6)} \quad y_t = \frac{w(\alpha_3, \alpha_4, \alpha_5)}{\overline{W}} + \varphi_t$$

where α_i are defined as above and ψ_t is a residual term with expected value zero. The base values used for the estimation are given in Table 4.

Table 4: Base parameter values

Value	Broadacre	Horticulture	Source
Demand Elasticity[a]	-0.52	-0.10	derived from McClintock et al (1998); Mues and Opalinska-Mania (1998)
Annual Average Use (GL)	1912	136	Mues and Opalinska-Mania (1998)
Base Water Price ($/ML)	20	20	Mues and Opalinska-Mania (1996)
Delivery Charge ($/ML)	9.35	9.35	Mues and Opalinska-Mania (1998)
Output Price[b] $	152	938	derived from McClintock et al (1998) and Mues and Opalinska-Mania (1998)
Water Loss (%)[c]	50	50	Pendlebury (1998), Hall et al (1994)

a) Derived from a linear approximation of a stepped demand relationship in McClintock (1998)
b) Derived as a gross margin per ML
c) Total loss in water from storage to farm.

The irrigation season in the southern MDB is between August and May, inclusive. In August there is either very limited or no irrigation. Observations in June, July and August were removed from the data set and the frequencies and integration limits of the estimation equation were adjusted accordingly. Estimates were obtained using a non-linear estimation procedure in MATLAB and the results are summarised in Table 5. The value for α_3 was set to 1 to enable unique estimation of other model parameters.

The R^2 for the first equation was 0.76 and for the second, 0.66. The first order correlation of the residuals was 17 per cent for the first equation and 21 per cent for the second. The standard error of the residuals was around 0.03 for each equation. While capturing the general seasonal pattern, the model tended to understate peak season demands as a proportion of annual demand.

Table 5: Farm parameter estimates

	Broadacre			Horticulture		
	estimate	10% CI	90%CI	estimate	10% CI	90%CI
α_1	0.983	-	-	0.327	-	-
α_2	0.002	-	-	0.010	-	-
α_3	1.000	-	-	1.000	-	-
α_4	-0.635	-0.660	-0.611	0.840	0.819	0.861
α_5	-5.761	-5.841	-5.681	-2.736	-2.804	-2.669
R^2	0.764			0.659		
σ^2	0.028	0.025	0.031	0.033	0.030	0.038

The residuals from the two models were used to derive a set of estimates for a stochastic process, which incorporates both spatial and temporal correlations. A simple first order model was fitted to the residuals from each equation

(A7) $y_t = \gamma_0 + \gamma_1 y_{t-1} + \varepsilon_t$

The results are summarised in Table 6.

Table 6: Farm residual estimates

Value	Broadacre			Horticulture		
	estimate	10% CI	90%CI	estimate	10% CI	90%CI
γ_0	-0.001	-0.005	0.004	-0.001	-0.006	0.004
γ_1	0.169	0.002	0.335	0.214	0.050	0.378
$\sigma(\varepsilon)$	0.027			0.033		

Data on the correlation between farm level demands for irrigation water are not readily available. However, the level of correlation between inflows at the Blowering and Burrinjuck storages was approximately 60 per cent, suggesting that climatic conditions would lead to a moderate to strong correlation in farm level demands. In specifying the stochastic farm level water demands, water requirements were assumed to be spatially correlated at 60 per cent with catchment inflows. The i^{th} farm level generating function is given by

$$\text{(A8)}\quad \begin{aligned} &\tilde{y}_{it} = \gamma_{i0} + \gamma_{i1}\tilde{y}_{it-1} + \gamma_2\left[x\sigma_i(\varepsilon_i) + \mu_i(\varepsilon_i)\right] + (1-\gamma_2)\left[z_i\sigma_i(\varepsilon_i) + \mu_i(\varepsilon_i)\right] \\ &x \sim N(0,1) \\ &z_i \sim N(0,1) \end{aligned}$$

A.5 The Pricing of Water held in Storage

In evaluating the availability and demand for water throughout the irrigation season, it is assumed that the price of water is chosen to maximise the sum of net farm revenue and water sales revenue, as in Beare, Bell and Fisher (1998). The determination of water prices under the allocation based operating system and the optimal release system are given in equation (A9).

$$\text{(A9)}\ price_t = \begin{cases} \beta_0 + \beta_1\left(V_{t,Blowering} + V_{t,Burrinjuck}\right) + \beta_2\cos^2\left(\dfrac{t\pi}{12}\right) & \textit{optimal pricing rule} \\ \\ \beta_0 + \beta_1\left(remaining\ allocation_t\right) + \beta_2\cos^2\left(\dfrac{t\pi}{12}\right) & \textit{allocation based rule} \end{cases}$$

where $V_{t,i}$ is the volume of water held in storage *i*, and *remaining allocation* is the megalitre quantity of water as yet unallocated in the current irrigation season, from the total annual allocation.

The precise form of the price equations is determined in the simulation model using a genetic search algorithm (see section A.6).

A.6 The Genetic Search Algorithm

The genetic search algorithm (GA) was used to determine the β coefficients in the water price equations (A9). The GA was implemented as described in Beare, Bell and Fisher (1998), Beare and Bell (1998) and Goldberg (1989). Specifically, the search was conducted over 50 generations using 60 population strings. The length of each string corresponds to the number of parameters to be estimated (in this case, three β parameters). Following Goldberg, a cross-over rate of 0.6 and mutation rate of 0.001 was used. The genetic algorithm requires a search range to be specified. The initial values selected for the search are given in Table 7. The estimates can be refined by subsequent narrowing of the search range.

Table 7: Search ranges for genetic algorithm

Variable	Minimum	Maximum
Constant Term	0	50
Volume and Allocation Terms	–0.1	0
Cosine Term	0	100

In the deterministic simulations, a single trial was conducted will all stochastic processes fixed at their respective mean levels. For the stochastic simulations, 50 random trials were conducted, with each generation selected against an independent set of random trials. However, the stochastic generating functions were identical for each population string and an identical random seed was used for each simulation.

References

Alaouze, C. 1991, ‘The optimality of capacity sharing in stochastic dynamic programming problems of shared reservoir operation’, *Water Resources Bulletin*, vol.27, no.3, American Water Resources Association, Maryland.

Beare, S., Bell, R. and Fisher, B. 1998, ‘Determining the value of water: the role of risk, infrastructure constraints and ownership’, *American Journal of Agricultural Economics*, vol.80, December.

Beare, S. and Bell, R. 1998, ‘Efficiency of water use and access rights to infrastructure’, *Australian Commodities Forecasts and Issues,* ABARE, 4.98, December.

Beare, S., Bell, R. and Harrison, S. 1999, ‘Stochastic optimal control in bio-economic simulations: a comparison of solution techniques’, ABARE paper to be presented at 43rd Annual AARES Conference, Christchurch, 20-22 January.

Department of Land and Water Conservation 1998a, ‘Water Sharing, the way forward. Enhancing and extending water trading in NSW’, NSW Water Reforms, NSW Department of Land and Water Conservation, Sydney, December.

Department of Land and Water Conservation 1998b, ‘Water Sharing, the way forward. NSW progress on the water reforms 1995 to 1998’, NSW Water Reforms, NSW Department of Land and Water Conservation, Sydney, December.

Simpson, P. and McLeod, T. 1995, *1994/95 Demand management in the Murrumbidgee Valley,* NSW Department of Water Resources, April.

Dudley, N. 1988, ‘A single decision-maker approach to irrigation reservoir and farm management decision making’, *Water Resources Research*, vol. 24, no. 5, pp. 633–40.

Dudley, N. and Musgrave, W. 1988, ‘Capacity sharing of water reservoirs’, *Water Resources Research*, vol. 24, no. 5, pp. 649–58.

Goldberg, D. 1989, *Genetic Algorithms in Search, Optimisation and Machine Learning*, Addison-Wesley Publishing Company, New York.

Gooday, J. 1997, River headwater flows — modelling the spatial and temporal correlations within a larger framework, ABARE paper submitted to ModSim 97, International Congress on Modelling and Simulation, Hobart, 8–11 December.

Hall, N., Poulter, D. and Curtotti, R. 1994, *ABARE Model of Irrigation Farming in the Southern Murray–Darling Basin*, ABARE Research Report 94.4, Canberra.

Imagine That, Inc. 1997, *EXTEND™ Simulation Software for the Next Millennium*, San José, California.

McClintock, A. and Gooday, J. 1998, A methodology for assessing the impact of water policy reforms: a case study of irrigated broadacre farming, ABARE paper presented at 42th

Annual Conference of the Australian Agricultural and Resource Economics Society, Armidale, January.

Mues C. and Opalinska-Mania M. 1998, Irrigated Agriculture: A socioeconomic profile of the Murray Darling Basin, *Australian Farm Survey Report*, AGPS, Canberra.

Murrumbidgee Irrigation 1997, *Murrumbidgee Irrigation Activities Report 1996/97.*

Pendlebury, P. 1998, NSW Department of Land and Water Conservation, Personal communication, Sydney, July.

Samaranayaka, D., Freeman, F. and Short, C. 1998, ‘Water trading in the Murray–Darling Basin – some preliminary observations’, in *Outlook 98*, Proceedings of the National Agricultural and Resources Outlook Conference, Canberra, 3–5 February, vol. 1, *Commodity Markets and Resource Management*, ABARE, Canberra, pp. 157–66.

Snowy Water Inquiry 1998, *Snowy Water Inquiry Appendix of Resource Materials (Part 2)*, 11 September.

The Math Works Inc. 1997, Statistics Toolbox User’s Guide for Use with MATLAB.